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PROJECT SQUID

SEMI-ANNUAL PROGRESS REPORT

1 OCTOBER 1977

AEROCHEM RESEARCH LABORATORIES, INC.
AERONAUTICAL RESEARCH ASSOCIATES OF PRINCETON, INC.
CALIFORNIA INSTITUTE OF TECHNOLOGY
UNIVERSITY OF CALIFORNIA, SAN DIEGO
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UNITED TECHNOLOGIES RESEARCH CENTER
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PROJECT SQUID HEADQUARTERS
CHAFFEE HALL
PURDUE UNIVERSITY
WEST LAFAYETTE, INDIANA

Project SQUID is a cooperative program of basic research relating to Jet Propulsion. It is sponsored by the Office of Naval Research and is administered by Purdue University through Contract N00014-75-C-1143, NR-098-038.

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OFFICE OF NAVAL RESEARCH, DEPARTMENT OF THE NAVY

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DURING THE PERIOD 1 APRIL 1977 TO 30 SEPTEMBER 1977
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(10) T. C. Adamson, F. Broward, Edgar P. Bruce, Franklin Carta, A. Dean

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PROJECT SQUID HEADQUARTERS
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PURDUE UNIVERSITY
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I. AERODYNAMICS AND TURBOMACHINERY

THREE DIMENSIONAL TRANSONIC FLOWS IN COMPRESSORS AND CHANNELS

The University of Michigan, Ann Arbor, Michigan
Subcontract No. 8960-10

Professor T.C. Adamson, Jr., Principal Investigator
Professor M. Sichel, Principal Investigator

Introduction

The work described here is concerned with a study of flow problems in three dimensional transonic channel flows, using asymptotic methods. Consideration of three dimensional channel flows is important because of the possibility of mixed supersonic and subsonic flow regions where two dimensional solutions are inadequate except in special cases. The analysis consists of an investigation of those parametric regimes where asymptotic methods may be employed to derive relatively simple solutions to the flow fields, or if not for the whole flow, at least in local regions where it is difficult to obtain numerical solutions (e.g., in the region of shock waves). In order to gain some experience in the problems to be met in the analysis, a model flow, consisting of a shear flow passing through a three

dimensional channel with a flow constriction has been considered first. Thus, the model flow problem contains the important features of a rotor flow, but in a simple geometry. Asymptotic methods have been used to reveal the various regions where the solutions derived from linearized equations are not uniformly valid, and where, therefore, nonlinear governing equations must be used. Since this is a model problem, the philosophy has been that simple approximate solutions suffice, i.e., that detailed numerical solutions are not called for.

Discussion

The model problem chosen for study may be interpreted as the flow through a linear cascade with the blades aligned parallel to the incoming flow. The symmetry boundaries upstream and downstream of the blades are replaced by walls, so that the flow field considered is that through a three dimensional rectangular channel with flow constrictions, corresponding to half blades, on opposite walls. The radial variation of the rotor tangential velocity component is accounted for by consideration of a linear gradient of the velocity entering the channel.

The essential features of the flow fields obtained, including conditions under which choking of the flow may take place even though

the flow through the minimum cross sectional area of the channel is mixed, but excluding effects of shock waves, have been presented in references 1 and 2. In addition, the inner regions at the blade leading edges, where bow shocks may occur, and at the plane of minimum cross sectional area, where singularities in the solution may occur, have been investigated and the proper governing equations in these regions have been derived. It has been shown that linearized governing equations hold in the major part of the flow field, but that there are cases for which nonlinear governing equations must be employed in the inner region at the minimum cross sectional area.

During the period covered by this progress report, work has been done on analyzing the flow field in the neighborhood of a shock wave and on the position of the shock wave for given downstream plenum pressure. The problem is more complicated than the usual channel flow-shock wave problem due to the fact that a strong gradient exists in the flow. That is, the flow entering the channel between the blades has a spanwise gradient and this gradient is carried through the blade region. Moreover, the case under consideration is one for which the shock wave meets the sonic surface in the channel; thus the shock wave does not extend completely across the channel, existing only in the supersonic part of the flow. As a result, disturbances downstream of the shock wave can affect the flow upstream of the shock, as opposed to the case where the shock wave extends completely across the channel.

As in the above mentioned problem areas at the blade leading edge and minimum cross sectional area, the analysis of the flow in the neighborhood of the shock wave involves an inner region enclosing the shock, in which nonlinear governing equations hold. Due to the large gradients in the incoming flow, the shock wave is not planar, and in fact the shock shape is found as part of the solution. The method of integral relations is being used to obtain approximate solutions in this inner region; these solutions are being found for a range of shock positions.

The effect of staggered blades on the solutions is also under consideration. The flow through a rotor will be studied next.

References

(1) Adamson, Jr., T.C., "Three Dimensional Transonic Shear Flow in a Channel," Transonic Flow Problems in Turbomachinery, eds. T.C. Adamson, Jr. and M.F. Platzer, Hemisphere Publishing Corporation, 1977, p. 70.

(2) Sichel, M., and Adamson, Jr., T.C., "Three Dimensional Transonic Flow in Channels," XIII Symposium on Advanced Problems and Methods in Fluid Mechanics, Olsztyn-Kortowo, September 5-10, 1977.

AXIAL FLOW FAN STAGE UNSTEADY PERFORMANCE

Applied Research Laboratory
The Pennsylvania State University
P. O. Box 30, State College, Pennsylvania 16801

Subcontract No. 8960-4

Edgar P. Bruce, Principal Investigator

Introduction

The objective of this research is to analyze the time-dependent interaction between the components of an isolated axial flow fan stage and a spatially fixed, circumferentially varying flow field. The major variables are reduced frequency; rotor blade space-to-chord ratio, stagger angle, mean angle of attack, and design loading level; and rotor-stator axial spacing.

The experiments are being conducted in the ARL Axial Flow Research Fan. This facility has a hub radius of 12.06 cm (4.75 inches), a hub-to-tip radius ratio of 0.442, and operates in the subsonic incompressible flow regime. The rotor and stator blades have a 10 percent thick C1 profile with a chord of 15.24 cm (6.00 inches) and an aspect ratio of unity.

Instrumentation available at present or under development consists of: (1) a strain gaged sensor mounted within one rotor blade which detects the time-dependent normal force and pitching moment developed on a mid-span blade segment, (2) hot-film sensors mounted on the suction surface of rotor and stator blades which detect the nature of the boundary layer, i.e., whether the instantaneous boundary layer flow is laminar, turbulent or separated; (3) dynamic total head probes; (4) two-element hot-film probes; and

(5) conventional three-dimensional directional probes. A system is being developed which will permit on-line analysis of all time-dependent signals by a digitizing, phase-lock averaging process.

Discussion

The unsteady normal force and pitching moment results obtained in the initial phase of this program at reduced frequencies from 0.22 to 2.08 have been documented in a Project SQUID report (Reference 1). Experiments were conducted during a previous reporting period whose objective was to extend the range of reduced frequencies covered by the uncambered, isolated rotor to a value of 5.0 with variations in space-to-chord ratio ($0.68 \leq /C \leq 2.03$), stagger angle ($35 \text{ deg} \leq \lambda \leq 55 \text{ deg}$) and mean angle of attack ($0 \leq \bar{\alpha} \leq 8 \text{ deg}$). Analysis of this data showed that the static sensitivity of the sensor employed in these tests was too low to permit an acceptably accurate definition of the unsteady force and moment coefficients. Consequently, a new sensor was designed with greatly increased static sensitivity, obtained by employing aluminum rather than stainless steel as the sensor material and by employing dynamic strain gages instead of conventional strain gages, at the expense of dynamic performance as measured by an acceptable reduction in natural frequency. Two of these new sensors are being calibrated at present. These sensors will be used in uncambered, isolated rotor tests at reduced frequencies from 2.0 to 5.0, and in tests with the cambered (λ=50.3 deg) free-vortex loading distribution rotor.

Facility commitments to other programs precluded Project SQUID testing during this reporting period. Consequently, our efforts were

directed toward improvements in our hardware, programs and procedures which will be of value when testing resumes in October 1977. These improvements included the sensor development work noted above and:

1) modification of our data analysis procedures to account for small interactions between the force and moment gage signals,
2) recalibration of the disturbance generating screens using 5-hole three-dimensional directional probes (this was accomplished on a non-interference basis with the scheduled programs),
3) calibration of a third three-dimensional directional probe, and
4) check-out of an on-line data acquisition/analysis system.

Reference

1. Bruce, E. P. and Henderson, R. E., "Axial Flow Rotor Unsteady Response to Circumferential Inflow Distortions," Project SQUID Technical Report PSU-13-P, September 1975.

INVESTIGATION OF THE EFFECTS OF HIGH AERODYNAMIC LOADING ON A CASCADE OF OSCILLATING AIRFOILS

United Technologies Research Center
East Hartford, Connecticut 06108
Subcontract 8960-19

Franklin O. Carta, Principal Investigator
Arthur O. St. Hilaire, Principal Investigator

Introduction

The basic objective of this research program is to study the phenomenon of dynamic stall on a cascade of oscillating airfoils. Measurements are being made of the unsteady chordwise pressure distribution, and efforts are being made to detect the occurrence of boundary layer transition and separation on the surface of an oscillating cascaded airfoil operating near the static stall condition.

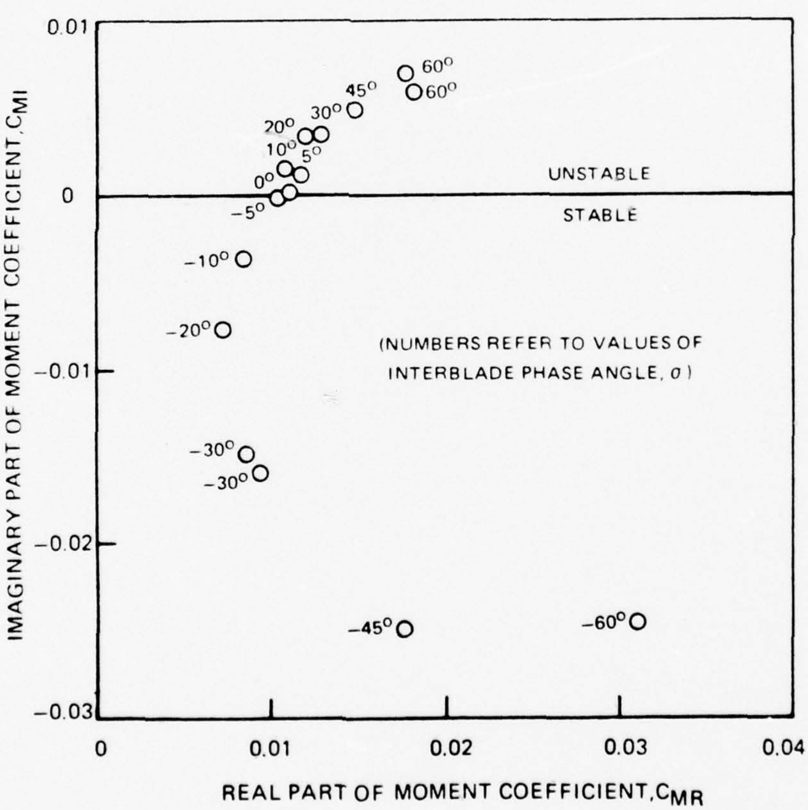
Program Review

The only actual work done under this contract during the past six months has been the preparation of the models for additional testing. However, a great deal of planning has been done, based on the results obtained from our related AFOSR program. In this work tests were performed at a fixed velocity of 200 ft/sec and

incidence angle of 8° over a modest range of frequencies and over an extensive range of interblade phase angle, from $\sigma = 60^\circ$ to $+60^\circ$. These data have been fully reduced and we have found that interblade phase angle has a very profound effect on the aerodynamic response of the airfoil. This is illustrated in the phase plane plot of Fig. 1 in which the imaginary part of the oscillatory moment coefficient, which determines the stability of the system, is plotted versus the real part for interblade phase angle varying from $\sigma = -60^\circ$ to $\sigma = +60^\circ$. In view of the strong dependence of the primary aerodynamic response of the blade on σ, it has been decided to redirect our experiment for our current contract to specifically study this effect for two other values of incidence angle. Approval for this change is pending, and the tests will begin soon.

PHASE PLANE STABILITY PLOT FOR OSCILLATING CASCADE AIRFOILS

VELOCITY = V = 200 FT/SEC
INCIDENCE = α_{MCL} = 8°
FREQUENCY = f = 17.1 CPS
REDUCED FREQUENCY = k = 0.134
GAP/CHORD RATIO = τ/C = 0.75
STAGGER ANGLE = β_1^* = 30°



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INVESTIGATION OF ADVERSE PRESSURE GRADIENT CORNER FLOWS

University of Washington, Seattle, Washington
Subcontract No. 8960-27

Professor F. B. Gessner, Principal Investigator
Mr. S. Ono, Research Assistant

Introduction

This research program is a comprehensive experimental study of developing incompressible turbulent flow along a streamwise corner in the presence of adverse pressure gradients. This type of flow exists in several engineering applications: for example, flow in rectangular diffusers and along intersecting surfaces such as wing-body junctions. The nature of flow in the corner region is complicated by the existence of transverse mean flows (secondary flows) which have a pronounced influence on local wall shear conditions and heating rates in the corner region. Under favorable pressure gradient flow conditions, these secondary flows are relatively weak (transverse mean velocities on the order of 1 to 2% of the local primary flow velocity) and the flow is in essentially local equilibrium [1]. For mild adverse pressure gradient flow conditions, the flow may not be in local equilibrium, and the corner region is prone to local flow separation [2].

In previous work by the Principal Investigator and his co-workers [3-5], a length-scale model was developed which can be used to predict local corner flow behavior for zero and favorable pressure gradient flow conditions. It is the intent of the present study to generate a body of data under adverse pressure gradient flow conditions which can be used to evaluate the adequacy of both zero-order (length scale) and second-order (transport equation) levels of closure. The data will include mean flow and Reynolds stress data for both unseparated and separated flow conditions.

Discussion

The variable divergence angle, rectangular diffuser discussed in the previous progress report has been modified to provide continuous (step-free) diverging walls. The transversing mechanism noted in that report has also been modified to provide probe translation in three mutually perpendicular

directions. Some comparative Reynolds stress measurements have been made in a calibration facility with two commercially available linearizers in order to select the one most appropriate for hot-wire measurements in the diffuser.

Reynolds stress measurements in fully-developed pipe flow are now being made to test the adequacy of the hot-wire response equations discussed in the previous progress report. These equations enable one to extract Reynolds stress data from inclined wire measurements in the presence of moderate transverse mean flows, a condition which is expected to exist in the corner region of the diffuser for moderate divergence angles. Special total pressure probes are also being fabricated in order to measure primary flow velocity profiles and local wall shear stress distributions in the corner region. It is anticipated that this phase of the work will be completed by October 1977 and that local corner flow measurements in the diffuser will begin shortly afterwards.

References

1. Gessner, F. B., Po, J. K., and Emery, A. F., "Measurements of Developing Turbulent Flow in a Square Duct," Proceedings of the 1977 Symposium on Turbulent Shear Flows, Pennsylvania State University, April 1977, pp. 9.1-9.10 (to be included in the Commemorative Proceedings of the First International Turbulent Shear Flow Symposium published by Springer-Verlag).

2. Mojola, O. O. and Young, A. D., "An Experimental Investigation of the Turbulent Boundary Layer Along a Streamwise Corner," AGARD CP-93, AGARD Symposium on Turbulent Shear Flows, 1972, pp. 12-1 to 12-9.

3. Gessner, F. B. and Emery, A. F., "A Reynolds Stress Model for Turbulent Corner Flows - Part I: Development of the Model," J. Fluids Engrg., Trans. ASME, Series I, Vol. 98, 1976, pp. 261-268.

4. Gessner, F. B. and Po, J. K., "A Reynolds Stress Model for Turbulent Corner Flows - Part II: Comparisions Between Theory and Experiment," J. Fluids Engrg., Trans. ASME, Series I, Vol. 98, 1976, pp. 269-277.

5. Gessner, F. B. and Emery, A. F., "A Length-Scale Model for Developing Turbulent Flow in a Rectangular Duct," J. Fluids Engrg., Trans. ASME, Series I, Vol. 99, 1977, pp. 347-356.

TRANSITORY STALL IN DIFFUSERS

Thermosciences Division
Department of Mechanical Engineering
Stanford University
Stanford, California 94305
Subcontract No. 8960-24

Professor James P. Johnston, Principal Investigator
Professor Stephen J. Kline, Principal Investigator
Mr. Jalal Ashjaee, Research Assistant
Mr. John Eaton, Research Assistant

Introduction

The general goal of this program is to study the transitory stall flow regime in two-dimensional diffusers. Maximum value of pressure recovery at fixed non-dimensional length, an important design optimum [1], generally occurs when the turbulent boundary layers are starting to separate or stall. The flow is rather unsteady and significant amounts of transient back flow already are seen in the diffuser at peak pressure recovery. These flow conditions are associated with the onset and development of the transitory stall flow regime [2].

Ghose and Kline [3] have developed a new, steady flow boundary layer prediction method which is solved simultaneously (not iteratively) with the inviscid core flow. This method gives surprisingly good agreement with data on pressure recovery up to, and slightly beyond the condition of peak recovery. The existing wall pressure data in this region are not of sufficient accuracy to properly check the method, however.

The primary objectives of our program are (i) to provide new mean and fluctuation velocity and pressure data in diffusers operating close to peak pressure recovery in order to complement, check, and provide a data base of sufficient accuracy to allow for possible improvement of the prediction method of Ghose and Kline [3], and (ii) to study the magnitude of the velocity and pressure fluctuations in the transitory stall regime in order to provide a useful extension of the work of Smith and Kline [2] and Layne and Smith [4].

Discussion

Work is proceeding in two areas, (i) the design and construction of a new diffuser wind tunnel and (ii) the investigation of methods for measurement of mean and fluctuating velocities and the Reynolds stresses in, and near, the zone of instantaneous flow separation.

The Diffuser Tunnel. (Refer to Fig. 1 in Progress Report, March 15, 1977). Most of the tunnel elements are complete with the exception of the test section which is now under construction. Reduction of airborne sound inside the system to a minimum and elimination of vibration from exterior sources have been major design criteria. The following paragraphs indicate our approach to design for these problems.

The exit plenum and the filter box are made of 3/4 inch plywood and are covered on the inside by 1 inch sound absorbing material to diminish sound reflectivity and hence to reduce the possibility of sound-flow interactions. The sound absorbing material used, Soundcoat's "Soundfoam", is claimed to be better than most at frequencies below 1 kHz. The same type of material in 1/2 inch thickness was used to cover the inside of the double expansion diffuser and all the inside walls of the return circuit elements, up to the extension ducts. The fan, New York Blower's "Acousta Foil 129", and the adjustable speed motor, Dynamic's ACM 9033, are mounted on a base isolated from the floor by neoprene pads. The fan and the motor are connected, through V-belts, to achieve a top fan speed of 4250 rpm. The combined system should give us our desired operational range: continuously adjustable air velocity of 40-150 ft/sec at the test section inlet (3"x12" area). The operating speed range lies above the unregulated speed range of the motor, 0-50 rpm, and the system's first resonance is designed to occur at a fan speed of 330 rpm. Within the operating speed range, the isolation transmissibility is not expected to exceed 1/3, the value estimated to occur at the lowest operating speed.

The double expansion diffuser (13-1/2"x9" inlet and 23-1/2" x 21-1/4" exit areas) is made out of 3/4 inch plywood and is vaned with 1/16 inch thick aluminum plates to enable it to yield a high pressure recovery in the unstalled flow regime. The return circuit (23-1/2" x 21-1/4" area) is made out of 1/2 inch plywood and it is braced externally for stiffness by 2"x4" pine flanges attached at 2-1/2 ft. intervals. It hangs from two parallel aluminum beams attached to the roof trusses of the laboratory. All three 90 degree corners in the tunnel circuit are vaned with Airsan's "acousti-turns": airfoil-shaped aluminum vanes perforated on the convex side and filled with fiberglass media in the inside to give a greater sound power reduction, and, hopefully to reduce the magnitude of low frequency standing waves in the 30 ft long retune air duct.

In order to avoid flow irregularities associated with screens of high solidity, five new screens (58 mesh and .004 inch wire diameter) with a solidity of 41.0% were installed at 2 inch intervals on the existing frame. Immediately upstream of the screens is a "honeycomb" made of 24070, plastic milk straws (4 mm diameter and 5-3/4 inch length) carefully packed in close packed array. The extension ducts upstream of the "honeycomb" are made of 1/2 inch plywood and, like the nozzle, screens and honeycomb are mounted on caster wheels.

As soon as our test diffuser is built and mounted in the tunnel circuit, and the shake down experiments are carried out, we will start on our next immediate objective: the collection of systematic mean velocity profiles at diffuser inlet and the measurement of wall pressure distributions for diffusers set at various opening angles in the unstalled and stalled flow regimes. These data will be compared to the UIM* prediction method of Ghose and Kline [3].

Prediction of Pressure Recovery and Separation. It is one of our objectives to check and possibly improve or extend the application domain of the UIM prediction method for the two-dimensional diffusers operating in the transitory stall regime. In the computer code, Ghose and Kline allow for calculation by one of two cases, 1-D or 2-D irrotational core.

We ran the program for our test diffuser at several opening angles, with the 1-D core model. The inlet boundary layers at the nozzle exit were assumed to be fully turbulent $(H=1.4)$ at a blockage factor, $2\delta^*/W = 0.050$. Core speed was 140 ft/sec, $W_1 = 3$ inches and $\nu = 1.57 \times 10^{-4}$ ft^2/s . The inlet had parallel walls as did the short downstream tailpipe.

The predicted variation of the pressure recovery coefficient along the diffuser wall is shown in Fig. 1. The small table on this figure shows the predicted and the ideal 1-D pressure recoveries and also the effectiveness values at the diffuser exit. Also, on this figure are shown the predicted locations of the intermittent separation $(H = H_{sep})$ and points of zero wall shear $(C_f = 0)$. In addition, reattachment locations are shown. However, it should be realized that the predicted reattachment points must be seriously questioned because Ghose and Kline never intended to predict reattachment, nor have any comparisons been made with the experimental reattachment data. A one-dimensional core model, with marching step solution, is not really expected to handle both separation and reattachment where large reverse flow regions are present. We will attempt to use the 2-D core model later in our comparisons with experiment.

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* UIM means unified integral method.

Measurement Techniques. We have ordered two channels of pulsed wire anemometry equipment and two probes from Malvern Instruments in Great Britain, the only commercial supplier of this equipment. The funds for these devices were obtained from other sources, but they will be available to us in 1978 at no cost to the project.

The pulsed wire system, hot wire anemometers, probe traversing devices, and other special instrumentation for use in transitory or unsteady turbulent separating flows is to be used jointly with another project whose goal is the study of the structure of turbulent flow at reattachment. Compatibility with the latter project is designed into our diffuser. For example, the instrument ports on our diffuser rig will be identical to those on the reattachment flow rig so that easy interchange of probes, traversing gear and wall plugs may be accomplished.

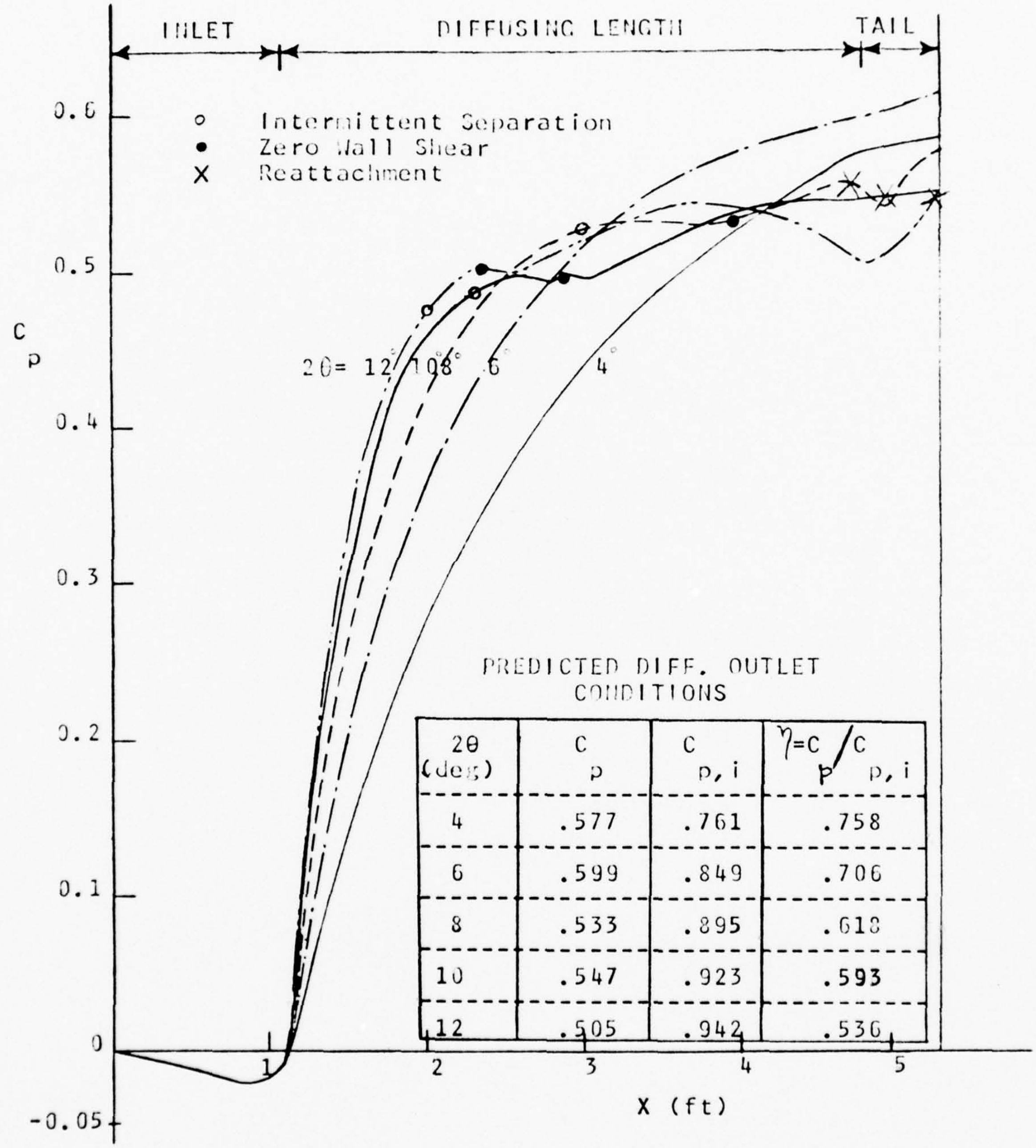
References

1. Sovran, G. and Klomp, E. D., "Experimentally Determined Optimum Geometries for Rectilinear Diffusers with Rectangular, Conical or Annular Cross-Section," Fluid Mechanics of Internal Flow, G. Sovran, Editor, Elseviier Publishing Co., 1967, pp. 270-319.

2. Smith, C. R., Jr. and Kline, S. J., "An Experimental Investigation of the Transitory Stall Regime in Two-Dimensional Diffusers Including the Effects of Periodically Disturbed Inlet Conditions," J. of Fluids Engineering, TASME, Vol. 96(I), pp. 11-15, 1974.

3. Ghose, S. and Kline, S. J., "Prediction of Transitory Stall in Two-Dimensional Diffusers," Report MD-36, Thermosciences Division, Mechanical Engineering Dept., Stanford University, December, 1976.

4. Layne, J. L. and Smith, C. R., Jr., "An Experimental Investigation of Inlet Flow Unsteadiness Generated by Transitory Stall in Two-Dimensional Diffusers," Tech. Report CFMTR 76-4, School of Mechanical Engineerng, Purdue University, August, 1976.



2θ (deg)	C_p	$C_{p,i}$	$\eta = C_p / C_{p,i}$
4	.577	.761	.758
6	.599	.849	.706
8	.533	.895	.618
10	.547	.923	.593
12	.505	.942	.536

Fig. 1. Predicted variation of pressure recovery for the test diffuser. Inlet blockage B=0.050, H=1.40, inlet velocity U_∞=140.0 ft/sec, kinematic vis-- cosity ν=1.567X10^{-4} ft^2/sec.

JA/JPJ
Sep. 1977

AN INVESTIGATION OF PRESSURE FLUCTUATIONS AND STALLING CHARACTERISTICS ON ROTATING AXIAL-FLOW COMPRESSOR BLADES

Virginia Polytechnic Institute
and State University, Blacksburg, Virginia
Subcontract No. 8960-13

Professor H. L. Moses, Principal Investigator
Professor W. F. O'Brien, Jr., Principal Investigator
Mr. R. R. Jones, Research Assistant
Mr. C. T. Jones, Research Assistant

Introduction

The overall goal of this research program is to provide a better understanding of stall-related phenomena in axial-flow compressors. The aspects of compressor performance that are of interest include the onset of stall, loss in performance, and the flow instabilities associated with stall.

The program involves both experimental and analytical efforts. A primary feature of the experimental work is the measurement of pressures directly on the rotor of test compressors, for flow conditions up to and including stall. For high-frequency-response measurements, special radio telemetry data transmission equipment has been developed for use with blade-mounted transducers. Average and slowly-varying pressure measurements are made employing a pressure scanner that has been adapted to rotate with the compressor rotor. Ports on the compressor blades are connected by tubing to the scanning valve. Pressure measurements are made by a single transducer located at the shaft center.

The current experimental work is being conducted on a relatively low-speed (~ 2400 rpm) one-or-two-stage axial-flow compressor. This facility permits fundamental investigations of the stalling behavior with a minimum of on-rotor instrumentation difficulties. A second facility provides for similar measurements with rotor speeds to 18,000 rpm.

Progress has been made in the development of a flow model that includes the essential features of stalling behavior. Fundamentally, the model includes provision for simultaneous, interactive calculation of the inviscid region and the boundary layer in a flow channel. Separated flows are thus included in the range of the model. Three-dimensional and unsteady effects are approximated.

Discussion

The technique for the simultaneous calculation of inviscid and boundary layer flows is reported in a paper which has been accepted for publication in the AIAA Journal [1]. The paper reports a general procedure for calculating the boundary layer simultaneously with the outer, inviscid flow. Integral equations for the boundary layer and finite-difference equations for the inviscid flow at a given longitudinal position form a linear set with a tridiagonal coefficient matrix. The set is solved simultaneously at each position, beginning at the upstream boundary and iterating over the flow field (successive line relaxation). Convergence of the procedure with separated flow is demonstrated by a numerical example. The free-stream velocity, boundary-layer displacement thickness, and wall shear stress are shown in the paper for three boundary layer profile assumptions.

In previous work, techniques for the approximation of end-wall boundary layer effects in compressor flow models have been developed. Progress has been made in relating the flow turning angle, or work, and the loss of performance to the boundary layer growth. The general direction of the present effort is to incorporate these additional compressor-related flow models with the simultaneous calculation technique. During the present reporting period, both power-law and logarithmic turbulent boundary layer profiles were incorporated into the theory. Work is continuing to include a modified-logarithmic profile model which will more accurately predict the backflow in the separated region. Also, provisions to accept boundary conditions and finite-difference grids representing compressor cascades are being incorporated. We are optimistic that the completed model will provide an improved ability to predict the stalling behavior of compressors. The model will be checked with results from both of the available compressor test rigs.

Experimental programs investigating surge, rotating stall and distorted inflow effects were conducted during the period. All were conducted on the low-speed compressor test facility. An investigation of blade pressure distributions during surge was conducted by Jones [2]. The machine was induced to surge by the use of a flexible, resonant discharge plenum. Rotor pressure distributions at three span positions were measured during surge. The operating path of the compressor system was experimentally determined and the blade pressure distributions were correlated to their point of occurrence during the surge cycle. A comparison of these pressure distributions with the blade pressure distributions obtained during steady state operation of the compressor at the same throttle position was presented.

Reports on the rotating stall and distorted inflow investigations are presently being completed. The rotating stall investigation was designed to study the structure and growth of the stall cell. In the distorted inflow tests, circumferential distortion screens of varying density were employed to study the induced stalling behavior.

Improvements were made to the high speed test facility described in Ref. 3. An all-electric starting system for the T-64 gas turbine drive engine was installed, replacing the previous diesel-driven system. An inlet silencer was designed and built to reduce compressor noise radiating from the front of the test cell.

References

1. Moses, H. L., Jones, R. R., O'Brien, W. F., and R. S. Peterson, "Simultaneous Solution of the Boundary Layer and Free Stream with Separated Flow," accepted for publication, AIAA J.

2. Jones, C. T., Blade Pressure Distributions During Surge of a Low-Speed Axial-Flow Compressor," M.S. thesis, VPI&SU, August 1977.

3. O'Brien, W. F., Moses, H. L., Jones, R. R., and Sparks, J. F., "The V.P.I. Gas Turbine and Turbomachinery Research Laboratory", ASME Paper No. 77-GT-73, 1977.

Semi-Annual Progress Report

EFFECTS OF TURBULENCE ON FLOW THROUGH AN AXIAL COMPRESSOR BLADE CASCADE

Colorado State University, Fort Collins, Colorado
Subcontract No. 8960-15

Professor Willy Z. Sadeh, Principal Investigator
Mr. Herbert J. Brauer, Research Assistant

Introduction

The long-term objective of this research program is to ascertain the role which oncoming turbulence can play in reducing the aerodynamic losses in flow through a blade cascade of an axial-flow compressor at moderate Reynolds numbers of order of 2×10^5 or smaller. At these Reynolds numbers prohibitively high losses and even fully stalled blades are induced by laminar separation of the profile boundary layer. Supply of oncoming turbulence of sufficient energy concentrated at scales commensurated with the thickness of the prevalent profile boundary layer can forestall the laminar separation. Suitable management of the turbulent energy distribution possesses, furthermore, the potential to even generate and sustain a fully attached turbulent boundary layer on the profile suction side. Accumulation of turbulent energy at the scales of interest can be produced by the selective amplification of turbulence. This selective turbulent energy intensification is governed by the vortex stretching mechanism characteristic to forward stagnation flow.

The first phase of this research program focuses on the investigation of the evolution of incoming turbulence and its interaction with the boundary layer in flow about a circular cylinder. This phase represents a diagnostic study regarding the selective amplification of turbulence through the vortex-stretching mechanism and the effects of the intensified turbulence on the body boundary layer.

Discussion

The current research effort has been concentrated on visualization of the flow within the stagnation zone of a circular cylinder. Basically, flow visualization represents an indispensable diagnostic tool in turbulent flow research. Visual observations can readily render invaluable physical insights into the patterns of turbulent flows in spite of their inherent limitations. In particular, the usefulness of visual techniques regarding identification of spatially coherent patterns of turbulence is currently recognized. Visualization possesses moreover the potential to supply approximate quantitative information concerning the spatial scale structure of turbulence. The limitations of flow visualization are related to the instantaneous interpretation and the two-dimensionality of the flow pictures. These intrinsic limitations are however overridden by the significant physical evidence provided by and the prompting of a better understanding of the coherent structure of turbulence due to the visualization.

The primary motivation for undertaking the visualization study was to outline the selective stretching mechanism, the tilting of vortex tubes and the accompanying turbulence amplification. An attempt at delineating the coherent vortex structure near the stagnation zone was concurrently carried out. An additional objective was to identify the interaction between the amplified turbulence and the body boundary layer.

The results of the extensive, albeit not exhaustive, visualization study are reported in a technical report titled "Flow visualization of vorticity amplification in stagnation flow" which will be published during September 1977. More than a hundred stills and about 610 m (2000 ft) of 16 mm motion pictures were taken. All the details concerning the experimental setup and the experimental procedure are discussed in the subject technical report. The visualization was conducted at a Reynolds number of $8x10^3$ using white smoke composed of titanium dioxide (TiO_2). By and large, the analysis of the flow events was a painstaking effort and extremely time consuming. The endeavor was, on the other hand, rewarding since the pictures provided comprehensive insights into the flow structure. In particular, the motion pictures were instrumental in furnishing an understanding as regards the time development of the stretching mechanism, the tilting of the vortex tubes and the interaction with the boundary layer. The motion pictures were shot at a speed of 24 frames per second and, hence, the time period of each frame was about 42 ms. Both the stills and the motion pictures were taken from three view angles-viz., side, top and rear views. Selected film strips within a continuous interval up to 800 ms at most (up to 20 frames) were analyzed for each view angle. For each single frame the pattern of the entrained smoke was traced from its magnified projected image. This was accomplished using a special motion picture projector equipped with a photo optical data analyzer which permitted the stopping of the action at any desired frame for close scrutiny. A frame by frame examination of each strip led to the acquisition of a reasonable quantitative interpretation of the flow structure in addition to supplying an in-depth qualitative apperception

of the flow pattern. As a result, the evolution both in time and space of the stretching and the accompanying effects were roughly ascertained. In outlining the time-space development an attempt was made to follow the evolution of a stretched vortex tube until its penetration into the boundary layer.

Four representative prints (6 times enlarged) of the frames surveyed are provided in Figs. 1 and 2. In the former figure two side view shots are shown while in the latter figure two top view prints are given. Their corresponding interpretative schematics adequately scaled are included in these two figures. In these sketches the scale, the system of coordinates and the total approaching velocity are also shown. In addition, the theoretical laminar boundary-layer thickness, which is 2.15 mm (0.084 in) at the corresponding Reynolds number of $8x10^3$, is indicated by a dotted line and the letter L.

The initial entrainment of the approaching smoke filament by a vortex tube near the stagnation zone is distinctly perceived in the side view (the view in the plane x_1x_2) shown in Fig. 1. Moreover, the stretching of the tube and its subsequent tilting around the cylinder are clearly observed. The penetration of the amplified turbulence into the laminar boundary layer and the generation of a turbulent boundary layer are discerned in the side views. In the accompanying explanatory schematics the gross thickness of the vortices projected in the x_1x_2-plane is marked by a broken line. It was estimated to be around 15 mm (0.59 in). A turbulent boundary layer about 8 to 10 mm (0.31 to 0.39 in) thick is expected. Thus, it is apparent that the amplified turbulence affects the nature of the boundary layer.

Striking illustrations of the stretching mechanism are provided by the top views (the view in the x_2x_3-plane) displayed in Fig. 2. The tubular pattern reveals distinctly the gradual decrease in the scale of the vortex tube induced by the stretching. Furthermore, the concurrent vorticity intensification is indicated by the acceleration of the smoke filaments along the observed circular patterns. This vorticity intensification is responsible for the amplification of turbulence in the x_2-direction, i.e., in the plane normal to the axis of the vortex tube. It is important to point out that the increase in the spinning of the entrained smoke filaments is best perceived in the motion pictures. The broken lines in Fig. 2 delimit the coarse scale of a vortex tube drawn beneath the cylinder.

Estimates of the scales of the vortex tubes in the interpretative sketches ranged from 4 to 30 mm (0.16 to 1.18 in). The neutral scale predicted by the vorticity-amplification theory for this flow situation is 5.6 mm (0.22 in). Thereby vorticity at scales larger than the neutral, which undergoes amplification, is present. Similar quasi-regular flow patterns were visualized along the stagnation zone at many other stations. This strongly suggests the existence of the anticipated coherent vortex flow structure near the stagnation zone. The embayment perceived on the left edge of the tubular structure in the second view in Fig. 2 is indicative of the presence of an adjacent vortex tube rotating

in the opposite direction. This feature offers further evidence regarding the occurence of the coherent flow pattern.

The interaction of the stretched vortex tube with the laminar boundary layer is also observed in the top views. One, therefore, can safely presume that turbulent energy is supplied to the laminar boundary layer. Continuous feeding of turbulent energy fosters the development and sustenance of a turbulent boundary layer.

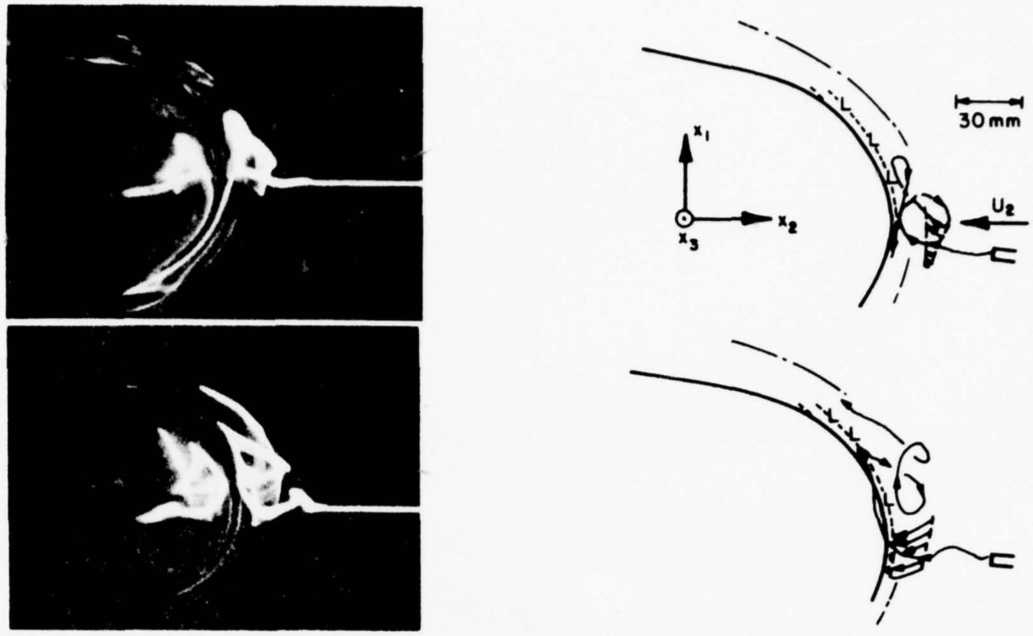


Fig. 1 Side view of the vortex flow pattern.

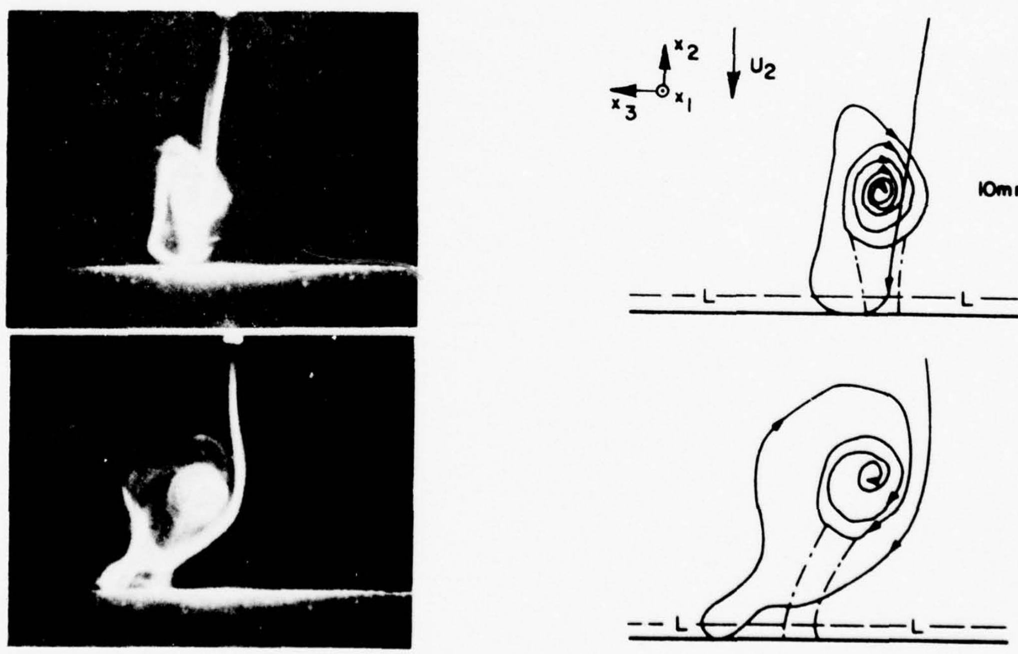


Fig. 2 Top view of the vortex flow pattern.

FUNDAMENTAL RESEARCH ON ADVERSE PRESSURE GRADIENT INDUCED TURBULENT BOUNDARY LAYER SEPARATION

Southern Methodist University, Dallas, Texas
Subcontract No. 8960-25

Professor Roger L. Simpson, Principal Investigator
Mr. C. R. Shackleton, Research Assistant
Mr. E. B. Bowles, Research Assistant

Introduction

The problem of turbulent boundary layer separation due to an adverse pressure gradient is an important factor in the design of many devices such as jet engines, rocket nozzles, airfoils and helicopter blades, and the design of fluidic logic systems. Until the last three years little quantitative experimental information was available on the flow structure downstream of separation because of the lack of proper instrumentation.

In 1974 after several years of development, a one velocity component directionally-sensitive laser anemometer system was used to reveal some new features of a separating turbulent boundary layer [1]. The directional sensitivity of the laser anemometer system was necessary since the magnitude and direction of the flow must be known when the flow moves in different directions at different instants in time [2]. In addition to much turbulence structure information, it was determined (1) that the law-of-the-

wall velocity profile is apparently valid up to the beginning of intermittent separation; (2) that the location of the beginning of intermittent separation or the upstreammost location where separation occurs intermittently is located close to where the free-stream pressure gradient begins to rapidly decrease; (3) that the normal stress terms of the momentum and turbulence kinetic energy equations are important near separation; and (4) that the separated flowfield shows some similarity of the streamwise velocity U, of the velocity fluctuation u', and of the fraction of time that the flow moves downstream [3].

Based upon these results, modifications [4,5] to the Bradshaw, et al. [6] boundary layer prediction method were made with significant improvements. However, this prediction effort pointed to the need to understand the relationship between the pressure gradient relaxation and the intermittent separation region structure. Another limiting factor for further refinement of the prediction of separated flows is the lack of fundamental velocity and turbulence structure information, especially in the backflow region. Thus, the objective of the current research program is to provide this information by using a directionally-sensitive laser anemometer system to determine quantitatively the turbulence structure of a separating, separated, and reattached turbulent boundary layer.

Discussion

This current research program was begun October 1, 1976, to obtain laser anemometer measurements of the separating flow of another adverse pressure gradient turbulent boundary layer for an airfoil or cascade blade type pressure distribution. Considerable effort has been made to avoid mean flow three-dimensionality. Specially designed wall suction and tangential wall jet boundary layer controls and peripheral equipment have been installed into the wind tunnel test section. The flow produced by these controls is two-dimensional within 1%.

Ciné films of laser illuminated smoke have clearly revealed the large eddy structure which supplies the near wall backflow. For this flow the unsteady nature of the turbulent-non-turbulent interface strongly interacts with the inviscid freestream to produce large inviscid freestream fluctuations before reattachment occurs downstream. This strong interaction is being further examined.

Measurements downstream of intermittent separation have confirmed the behavior of hot-wire anemometers in this region. A novel hot-wire anemometer circuit design is being employed to allow use of the split-film anemometer probe near the wall.

References

1. Simpson, R. L., Strickland, J. H., and Barr, P. W. (1974), "Laser and Hot-film Anemometer Measurements in a Separating Turbulent Boundary Layer," Thermal and Fluid Sciences Center, Southern Methodist University, Report WT-3; NTIS AD-A001115.

2. Simpson, R. L. (1976), "Interpreting Laser and Hot-film Anemometer Signals in a Separating Boundary Layer," AIAA Journal, 14, pp. 124-126.

3. Simpson, R. L., Strickland, J. H., and Barr, P. W. (1977), "Features of a Separating Turbulent Boundary Layer in the Vicinity of Separation," J. Fluid Mech., 79, pp. 553-594, 9 March.

4. Simpson R. L. and Collins, M. A. (1977); "Prediction of Turbulent Boundary Layers in the Vicinity of Separation," AIAA Journal (in press).

5. Collins, M. A. and Simpson, R. L. (1977); "Flowfield Prediction for Separating Turbulent Shear Layers," AIAA Journal (in press).

II. COMBUSTION AND CHEMICAL KINETICS

A SHOCK TUBE STUDY OF H_2 AND CH_4 OXIDATION WITH N_2O AS OXIDANT

University of Missouri, Columbia, Missouri
Subcontract No. 8960-21

Prof. Anthony M. Dean, Principal Investigator
Dr. Edward E. Wang, Research Associate
Mr. Don C. Steiner, Research Assistant

Introduction

The study of oxidation reactions in shock tubes has been stimulated by the use of fast, accurate numerical integration routines. Now it is possible for kineticists to more definitively test various oxidation mechanisms by a detailed comparison of calculated and observed concentration-time profiles. Although the $H_2/O_2/Ar$ and $H_2/O_2/CO/Ar$ systems have been successfully studied by this approach, extension to even simple hydrocarbon systems like CH_4/O_2 has been limited by lack of reliable high temperature rate constants. A common practice has been to extrapolate low temperature flow system data to the temperature range of interest. Unfortunately this approach can lead to serious errors; recent studies have convincingly demonstrated that many reactions of importance in combustion mechanisms exhibit markedly "non-Arrhenius" rate constants. In this light it appears to be most desirable to measure rate constants in the same high temperature regime where they will be used to test the combustion mechanisms. However, it is equally important that these data be obtained from relatively simple systems where assignment of the desired rate constant is not contingent upon proper assignment of a complex mechanism and the associated rate constants.

One such system results from the substitution of N_2O for O_2 in combustion studies. Recent work in this laboratory [1] showed that N_2O is a particularly useful source of oxygen atoms between 2000-3000 K. Thus, a study of combustion systems where N_2O replaced O_2 should provide useful information about rates of oxygen atom reactions at high temperatures. The primary advantage of N_2O as an oxidant is that oxygen atom reactions will occur in an environment where the concentration of molecular oxygen is much less than a normal combustion system; this considerably simplifies the kinetic analysis. Prudence dictates that such a substitution first be tested on a known system. For this reason our first efforts in the SQUID program utilized hydrogen as the fuel molecule.

To analyze the hydrogen system, data were collected from an extensive series of experiments on both $H_2/O_2/CO$ and $H_2/N_2O/CO/Ar$ systems. The results from the $H_2/O_2/CO/Ar$ work could then be coupled with those obtained earlier on N_2O dissociation to characterize the most important reactions in the $H_2/N_2O/CO$ system. If the N_2O profiles were found to yield values for the rate constant of the reaction $O + H_2 \rightarrow OH + H$ consistent with that obtained from the extensively studied H_2/O_2 system, it would suggest our approach is valid and that N_2O substitution is a useful technique for obtaining high temperature rate constants for oxygen atom reactions. With such confirmation, one is in a much more secure position to consider the methane system. Methane is of particular interest because of its widespread use in practical combustion systems. Furthermore, it is clear that many of the details of the combustion of more complex hydrocarbons will be similar to methane; characterization of these mechanisms will be significantly simpler once methane is thoroughly understood.

Discussion

During the last six months our studies of the $H_2/O_2/CO/Ar$ and $H_2/N_2O/CO/Ar$ have been completed [2]. There were two significant aspects of this work:

(1) The agreement achieved between the N_2O and O_2 systems demonstrated that our approach was valid.

(2) It was possible to obtain a high temperature measurement of the rate constant for the reaction $H + N_2O = OH + N_2$. Comparison to recent data at lower temperatures suggests this is another example of a "non-Arrhenius" rate constant.

Work has also been started on the methane system. In particular, data has been collected on the following systems: (1) $CH_4/N_2O/CO/Ar$, (2) $C_2H_6/N_2O/CO/Ar$, (3) $CH_2O/N_2O/CO/Ar$, and (4) CH_2O/Ar. Preliminary analysis of (1) has suggested values of the rate constant for the reaction $O + CH_4 \rightarrow CH_3 + OH$ in good agreement with that recently reported [3]. It is significant that these values are well above what one would expect from a simple low temperature extrapolation; in turn this suggests that values currently used in most methane oxidation simulations are too small. Detailed comparisons of calculated and observed profiles in this work indicate unsuspected complexities in the oxidation mechanism below 2200 K. (Data were collected over the range $1900 \leq T \leq 2900$ K.) Analysis of (2) has shown this feature cannot be attributed to reactions of methane itself. (At the temperatures of interest, C_2H_6 rapidly dissociates and we can observe the chemistry of the methyl radical in these experiments.) Thus we studied (3) and (4) to obtain more direct information concerning the high temperature chemistry of formaldehyde (CH_2O). Analysis of this data is still incomplete, but we now believe that this data will yield sufficient information to allow

us to understand the low temperature (i.e., $T \leq 2200$ K) behavior observed in the methane system. At this stage it would appear the methane studies have yielded an unexpected dividend: Clarification of the low temperature mechanism in the N_2O/CH_4 system should yield information directly applicable to the CH_4/O_2 system.

Notes and References

1. A.M. Dean and D.C. Steiner, J. Chem. Phys., 76, 598 (1977). (Project SQUID Technical Report UMO-1-PU. Earlier N_2O work is referenced here.)

2. A.M. Dean, D.C. Steiner, and E.E. Wang, Project SQUID Technical Report UMO-2-PU. (To be published in Combustion & Flame.)

3. P. Roth and T. Just, Ber. Bunsenges Physik. Chem., 81, 572 (1977).

COMBUSTION KINETICS AND REACTIVE SCATTERING EXPERIMENTS

Yale University, New Haven, Connecticut
Subcontract No. 4965-16

J.B. Fenn, Principal Investigator
N. Abuaf, B. Halpern and H. Tien

Introduction

The combustion of hydrocarbon fuels has been man's most used source of useful energy for much of this century. The chemical reactions which it involves have been among the most studied. And yet, there remains uncertainty as to the nature of the first reactive step in the complex sequence of reactions by which oxygen and hydrocarbon molecules become hot combustion products. This investigation comprises an attempt to identify that first reactive event and to determine its cross section by means of molecular beam scattering methods. The prospective advantage of such methods is that they can examine the consequences of a single collision between individual molecules. By the same token they are substantially limited in their ability to probe intermediate reaction steps which involve species of transient existence such as free radicals not readily obtainable as beams. In addition to this new venture in combustion kinetics we have been continuing a study of the evaporation and combustion of arrays of droplets. This study is based on an adaptation of the method of images which has been successful in solving Laplace's equation as it applies to electrostatic problems involving arrays of charged particles.

Discussion

A. Reactive Scattering. The cross sections of the first reactive steps in the combustion process are probably substantially smaller than those for which molecular beam methods have thus far been most effective. Consequently, we must achieve much higher detection sensitivities than have been usual in molecular beam experiments. Our approach is to employ uncollimated beams comprising free jets from small sonic nozzles exhausting into an evacuated region. The idea is to oppose a jet of hydrocarbon molecules with a jet of oxygen molecules. After collision the molecules and any product species will be trapped cryogenically or on adsorbents. Collection will continue for suitably long periods of time. Then the reaction chamber will be isolated and heated so that the trapped species return to the gas phase and can be swept out by a stream of helium for analysis by gas chromatography. We have already used variations of these techniques with some success in the study of molecule surface reactions and in molecular energy transfer during gas-gas molecular collisions at high velocity. The new feature is the trapping and collection of product flux for subsequent analysis.

Thus far in this new program we have built the reaction system. It comprises a pair of nozzle sources heated electrically and separated from the reaction zone by cooled radiation shields so that no hot surfaces will be accessible by reactant molecules after they issue from their source nozzles. These two nozzles are 30 μm in diameter and oppose each other at distances variable up to about four inches in a circular reaction chamber 15 cm in diameter and 20 cm high which is evacuated by a four-inch

diffusion pump. Between the reaction chamber and the pump are a four-inch valve and a trap which can be pumped on the liquid nitrogen side so as to achieve temperatures as low as the freezing point of nitrogen, 63.3 K. By our calculations this temperature will be low enough to trap cryogenically any hydrocarbons containing three or more carbon atoms and their likely initial products.

We have been checking out the sample recovery system and have found that run times of several hours are necessary to accumulate sufficient product so that there would be useful sample gas pressures (a few torr) in the reaction chamber after closing the valve and warming the trap. In order to decrease the running time we have resorted to external liquid nitrogen trap in which we condense the sample gas. The volume of this trap is only a few cubic centimeters so that after isolating and warming the product gas pressure is several tens of torr, sufficiently high to sample from with a gas syringe for injection in the chromatograph.

We think it fairly likely that an important first product of the first reactive step between a paraffin hydrocarbon molecule and an oxygen molecule may be an olefin. Therefore, we have also been checking out the chromatography of butane samples containing traces of butene. It becomes quite clear, as we had expected, that fractionation of the "crude" product will be desirable if not necessary in order to enhance the detectability of traces of olefin in unreacted paraffin. After examining several possibilities we are trying to take advantage of the ability of gold surfaces to chemisorb olefins. Thus, we deposit gold from a heated filament on the inside surface of the external trap.

After gentle warming to vaporize the paraffin we will fill the bulb with helium and heat the walls to drive the chemisorbed olefin into the gas phase.

It seems appropriate to mention some recent experimental observations which provide confirmation of our earlier SQUID work on the calibration of a mass spectrometer for the determination of true dimer concentrations in freely expanding supersonic jets. Our results indicated that in ionization by electron bombardment the yield of monomer ion from neutral monomer was as much as 10 times the yield of dimer ion from neutral dimer. Previous studies had assumed that the yield of dimer ion was twice that of monomer ion. Thus, it would seem that neutral dimer concentrations in such jets may be ten to twenty times higher than had been thought. Recently, we have made some careful measurements of the total cross section for the scattering of an argon beam by argon target molecules. We found that the apparent total cross section increased with increasing source pressure. This pressure dependence in conjunction with some results by van Deursen et al. on the relative scattering cross section of argon dimer and argon monomer made it possible to infer the dimer concentration in the argon beam(1). The results, in excellent agreement with those obtained mass spectrometrically, increase our confidence in the calibration procedure.

References

1. van Deursen, van Lumig and J. Reuss, Int. J. Mass Spectrometry and Ion Physics, 18, 129 (1975).

HIGH-TEMPERATURE FAST-FLOW REACTOR CHEMICAL KINETICS STUDIES

AeroChem Research Laboratories, Inc., Princeton, NJ 08540
Subcontract 8960-16

Arthur Fontijn, Principal Investigator

Introduction

Reliable quantitative knowledge of the kinetics of free metal atom and metal oxide species is required for a better understanding and description of (i) the burning of metallized propellants and (ii) the exhaust properties of rockets using such propellants. Suitable techniques for obtaining such kinetic information were unavailable until we adapted the tubular fast-flow reactor technique to reach temperatures up to 2000 K (1). This development has extended an essentially room temperature technique to being capable of being used for making measurements in the temperature range of conventional high-temperature techniques such as flames and shock tubes.

The agreement between (extrapolated) rate coefficients obtained from high and low temperature determinations by separate techniques is often poor. It is also becoming apparent that, for many reactions, Arrhenius-type plots of rate coefficients vs. T covering ranges on the order of 1000 K or more show distinct upward curvature with increasing T (e.g. Refs. 2-4), thus making extrapolation of k(T) data over wide temperature ranges a procedure of doubtful validity. For reliable k(T)

measurements it is desirable to use a single technique to span the entire T-range of interest. For the 300-2000 K range our high-temperature fast-flow reactor (HTFFR) technique provides such a technique for the first time.

Discussion

In the first half of the present contract year experiments were initiated on the reaction

$$Al + SO_2 \rightarrow AlO + SO \qquad [1]$$

The reasons for studying this reaction and the status of this work have been discussed in the preceding semi-annual report. Essentially all funding available in the present contract year was expended in this preceding six month period, so that no new data can be reported and no further discussion appears warranted here.

During the report period Ref. 4 was accepted for publication.

References

1. Fontijn, A., Kurzius, S.C., Houghton, J.J., and Emerson, J.A., "Tubular Fast-Flow Reactor for High-Temperature Gas Kinetic Studies," Rev. Sci. Instr. 43, 726 (1972).

2. Westenberg, A.A. and deHaas, N., "Rates of CO + OH and H_2 + OH Over an Extended Temperature Range, " J. Chem. Phys. 58, 4061 (1973).

3. Rawlins, W.T. and Gardiner, W.C., "Rate Constants of OH + OH $\rightarrow$ H_2O + O from 1500 to 2000 K," J. Chem. Phys. 60, 4676 (1974).

4. Fontijn, A. and Felder, W., "HTFFR Kinetics Studies of Al + CO_2 $\rightarrow$ AlO + CO from 300 to 1900 K, A Non-Arrhenius Reaction," AeroChem TP-353, March 1977, Project SQUID AC-16-PU, J. Chem. Phys. 67, 1561 (1977).

EXPERIMENTAL AND THEORETICAL STUDIES OF MOLECULAR COLLISIONS AND CHEMICAL INSTABILITIES

Massachusetts Institute of Technology, Cambridge, Massachusetts
Subcontract No. 4965-10

Professor John Ross, Chief Investigator
Dr. I. Procaccia
Mr. Randolph Burton

Introduction

The research program is concerned with theoretical and experimental studies of molecular collisions in reactive and non-reactive systems, and theoretical and experimental studies of chemical instabilities.

Discussion

A. Chemical Instabilities

We have succeeded in obtaining necessary and sufficient thermodynamic conditions of instability of time-dependent processes, as flow and chemical reactions. We start with given macroscopic kinetic (rate) equations and postulate that the entropy of the system, subject to the stated constraints of the kinetic equations, is a maximum. From that postulate we derive thermodynamic equations of motion which yield the conditions for stationary states, marginal stability, and relative stability where multiple stationary states exist. The work has been accepted for publication in the Journal of Chemical Physics.

In collaboration with M. Wrighton and N. Bose, we have studied experimentally an oscillatory photochemical reaction. A dilute solution (5 ppm) of dimenthylanthracene in CCl_4 or $CHCl_3$, when irradiated in a spectrofluorimeter with 260 nm shows marked and highly non-linear

oscillations in emitted fluorescence (420 nm). The oscillations disappear in a stirred solution which shows that they depend on a coupling of reaction and diffusion in and out of the irradiated region. The work has been published in the Journal of the American Chemical Society. Theoretical work on this fascinating phenomena is in progress.

B. Macroscopic Kinetics

We have made a series of measurements on the reactions of photoexcited NO_2 with cyclopropane and SO_2. Photoexcited NO_2 exists in a mixture of states corresponding to electronic excitation and isoenergetic high vibrational excitation of the ground electronic state. The reaction of NO_2 with cyclopropane yields the main products of ethylene and formaldehyde. Rate studies are in progress and need to be completed. The reaction of photoexcited NO_2 with SO_2 yields macroscopic white particles, likely copolymers of SO_2, NO_2, SO_3, NO. Rate studies have been made on this system and an article on the SO_2 work has been submitted to the Journal of Chemical Physics.

C. Chemical Dynamics

We have continued our work on testing the utility of a Franck-Condon approach to the study of the dynamics of chemical reactions. For the cases of reactions $F + H_2$, $F + D_2$, $H + Cl_2$, where exact calculations are available for comparison, we have evaluated numerically Franck-Condon overlap integrals for transition matrix elements and find that this simple approach gives all the correct trends with energy variation, final state variation, and initial state variation.

We are also applying the Franck-Condon approach to a study of angular distributions of reaction products and its dependence on product translational energy. Interesting experimental correlations have been observed and we are using our theory to search for useful interpretations.

Finally, we are using the Franck-Condon approach for a study of electronic transitions in atom-atom and atom-diatomic molecule encounters. We are finding that a simple model leads to very satisfactory results. The work needs to be finished and written up for publication.

Publications

1. "Remarks on Chemical Instabilities," Proceedings of the XVIth Solvay Conference, to appear in Advances in Chemical Physics, Wiley-Interscience, N. Y., John Ross.

2. "Instability and Far-from-equilibrium States of Chemically Reacting Systems," to appear in Advances in Chemical Physics, P. Hanusse, P. Ortoleva and John Ross.

3. "Stochastic reduction for dynamics of reactions with complex formation". Accepted for publication in J. Chem. Phys., David J. Zvijac, Shaul Mukamel and John Ross.

4. "A Basis for Orbital Symmetry Rules," accepted for publication in Angew. Chemie, Horia Metiu, George M. Whitesides and John Ross.

5. "Aperiodic and Periodic Oscillations in Fluorescence Intensity from Irradiated Chlorocarbon Solutions of Anthracene and 9, 10-Dimethylanthracene," J. Am. Chem. Soc. 99, (1977).

6. "Stability and relative stability in reactive systems far from equilibrium. I. Thermodynamic analysis," accepted for publication in J. Chem. Soc., Itamar Procaccia and John Ross.

7. "Stability and relative stability in reactive systems far from equilibrium. II. Kinetic analysis of relative stability of multiple stationary states," accepted for publication in J. Chem. Phys., Itamar Procaccia and John Ross.

8. "Statistical Mechanical Theory of the Kinetics of Phase Transitions," to appear in Adv. Stat. Mech., H. Metiu, K. Kitahara and John Ross.

Lectures

The principal investigator presented invited lectures at:

Rutgers University
Brooklyn Polytechnic Institute
University of West Virginia
International Workshop on Synergetics, Germany
Sixth Canadian Conference on Theoretical Chemistry
Battelle School on Physical Science in Biology

III. MEASUREMENTS

TURBULENCE MEASUREMENTS

IN JETS FLAMES AND COMBUSTORS

Polytechnic Institute of New York
Aerodynamics Laboratories

Subcontract No. 8960-5

S. Lederman - Principal Investigator

Introduction

In the last semiannual report of March 14, 1977 the enlarged and updated Raman and Laser Doppler data acquisition system was described and used to acquire concentration temperature and velocity profiles in a coaxial flame. Using appropriate data processing, turbulence intensity, concentration and temperature fluctuation as well as the mixedness parameter of N_2 and CO_2 in the flame were obtained. In this reporting period, additional data concerning the coaxial flame were obtained and some numerical work has been continued in an attemp at correlating the acquired experimental data with the available turbulence models of a coaxial turbulent flame.

Discussion

Since the inception of the program dealing with the development of nonintrusive diagnostic techniques applicable to flow fields and combustion, several versions have been constructed and applied towards acquisition of concentration of species (1-6) temperature profiles (3-6) velocity profiles (6-7) turbulence intensities (7-12). With the latest expansion of our data acquisi-

tion capabilities it has become possible to acquire simultaneously velocity and turbulence information for specie concentrations, and concentration fluctuation, as well as two specie concentrations, their temperature and concentration and temperature fluctuation. Due to the basically short pulse duration of the laser pulse utilized and the simultaneous acquisition of the concentration data, it is possible to obtain the mixedness parameter in diffusion flows or flames. This capability may be of importance in turbulence modeling.

Fig. 1-6 present some of the data acquired recently. Fig. 7-12 indicate the axial profiles of the flame.

References

1. Lederman, S. and Bornstein, J.: "Specie Concentration and Temperature Measurements in Flow Fields". Technical Report No. PIB-31-PU, March 1973.

2. Lederman, S. and Bornstein, J.: "Application of Raman Effect to Flow Field Diagnostics". Progress in Astronautics and Aeronautics, 34, "Instrumentation for Airbreathing Propulsion".

3. Lederman, S. and Bornstein, J.: "Temperature and Concentration Measurements on an Axisymmetric Jet and Flame". Technical Report No. PIB-32-PU, December 1973.

4. Lederman, S., Bloom, M. H., Bornstein, J. and Khosla, P.K.: "Temperature and Specie Concentration Measurements in a Flow Field". Int'l J. Heat and Mass Transfer, December 1974.

5. Lederman, S.: "Raman Scattering Measurements of Mean Values and Fluctuations in Fluid Mechanics". Laser Raman Gas Diagnostics ed. by M. Lapp and C. M. Penney, Plenum Press, N.Y., pp. 303-310, 1974.

6. Khosla, P. K. and Lederman, S.: "Motion of a Spherical Particle in a Turbulent Flow". Polytechnic Institute of New York, PIBAL Report No. 73-22, November 1973.

7. Lederman, S., et al.: "Temperature Concentration and Velocity Measurements in a Jet and Flame". Technical Report No. PIB-33-PU, November 1974.

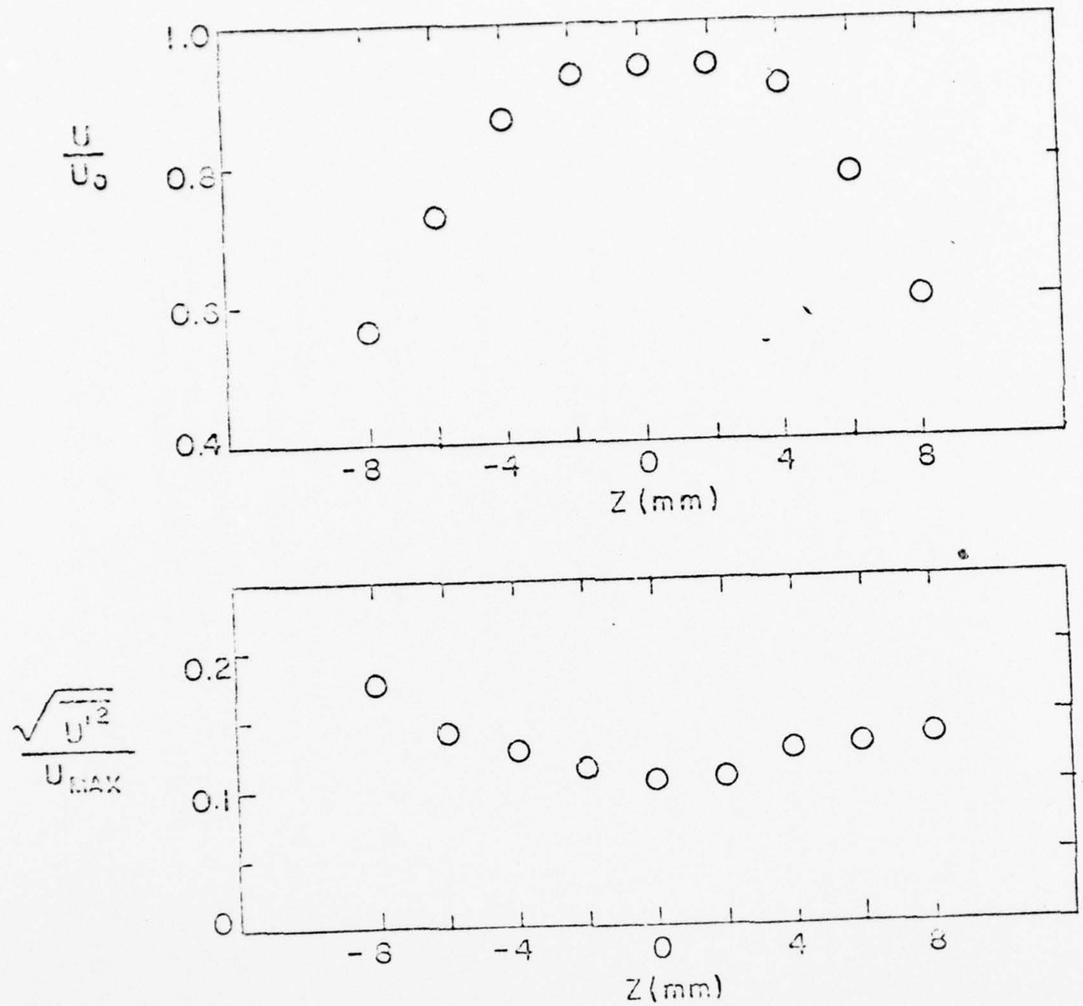
8. Lederman, S.: "Modern Diagnostics of Combustion", AIAA Paper No. 76-26.

9. Lederman, S.: "Some Applications of Laser Diagnostics to Fluid Dynamics", AIAA Paper No. 76-21.

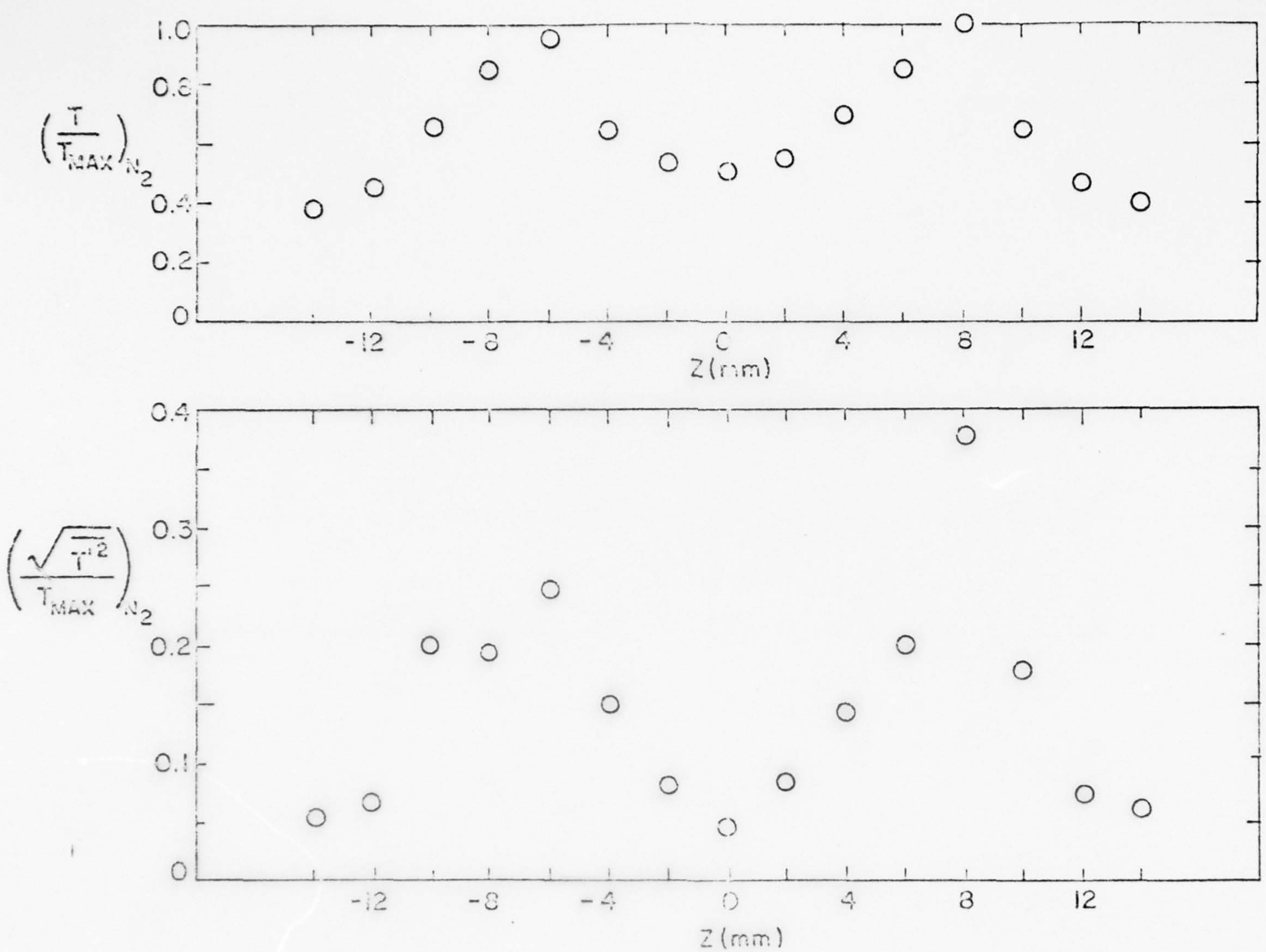
10. Lederman, S.: "Experimental Techniques Applicable to Turbulent Flows". AIAA Paper No. 77-213, Los Angeles, Calif.

11. Lederman, S.: "Temperature, Concentration Velocity and Turbulence Measurement in Jets and Flames". Technical Report No. PINY-76-10 December 1976, Project SQUID, Purdue University.

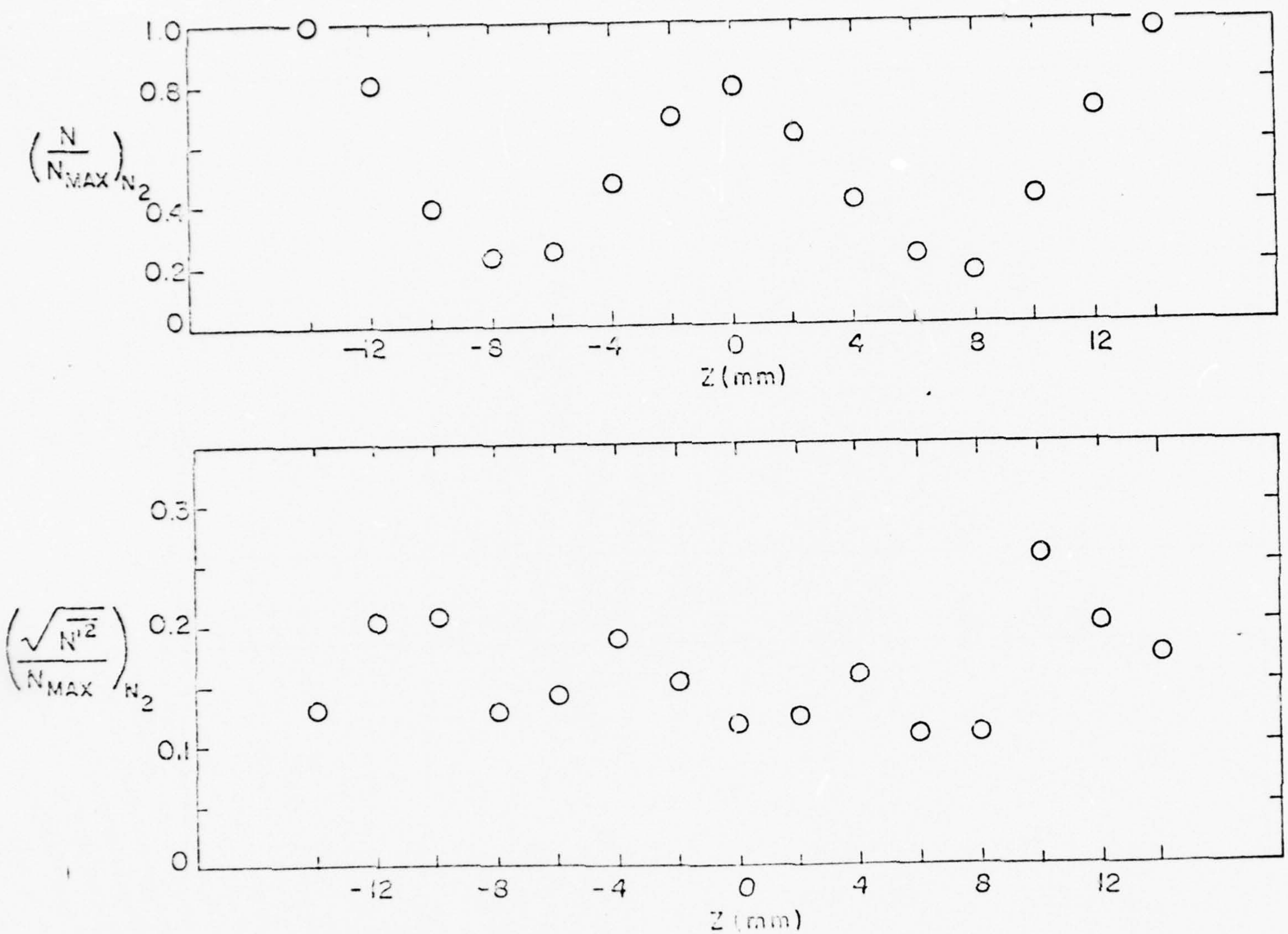
12. Lederman, S.: "The Use of Laser Raman Diagnostics in Flow Fields and Combustion". Progress in Energy Comb. Sci., 3, pp. 1-34, 1977, Pergamon Press.



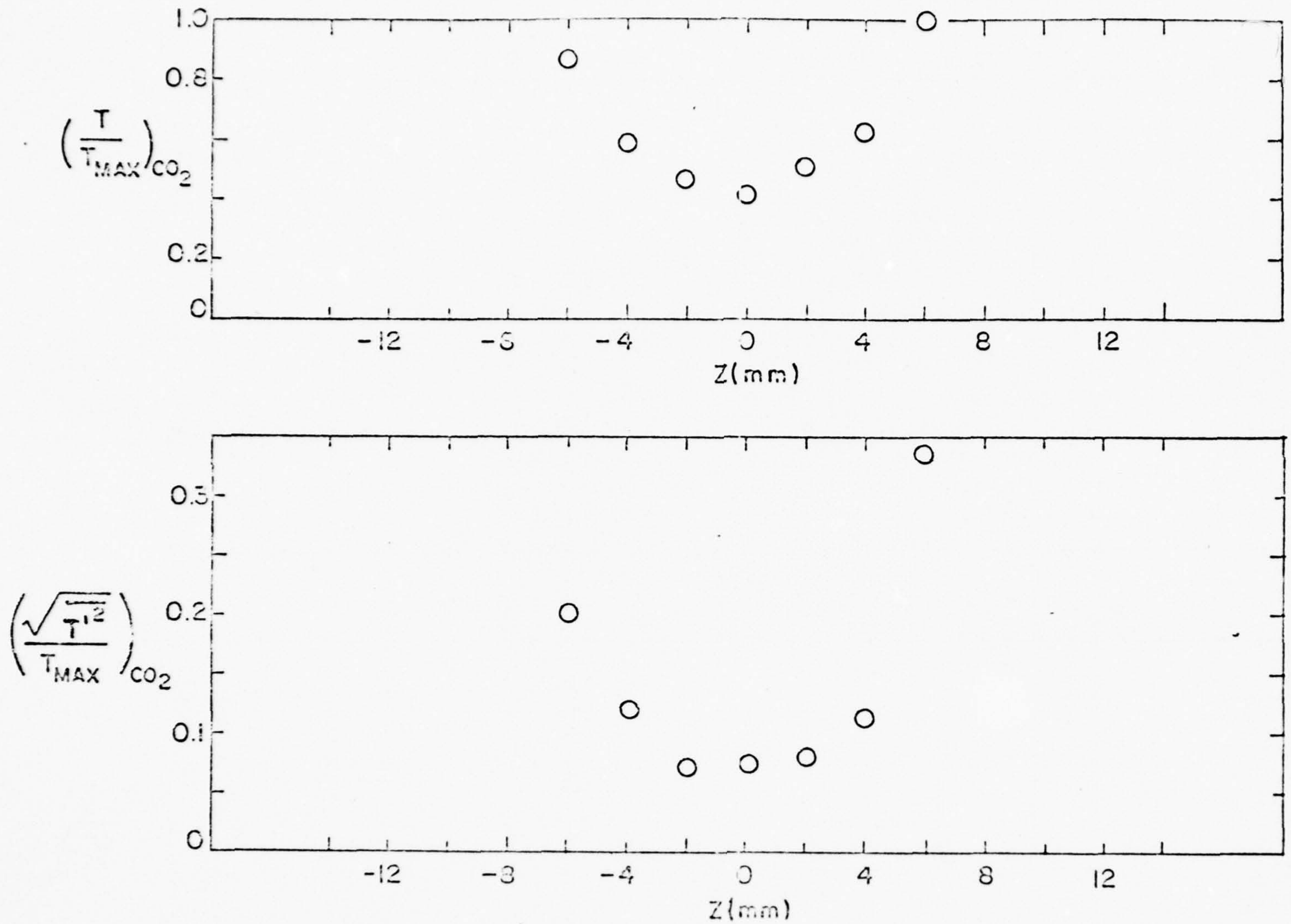
I FLAME RADIAL VELOCITY PROFILE AT X/D = 4.546, U_0 = 44.99 FT/SEC



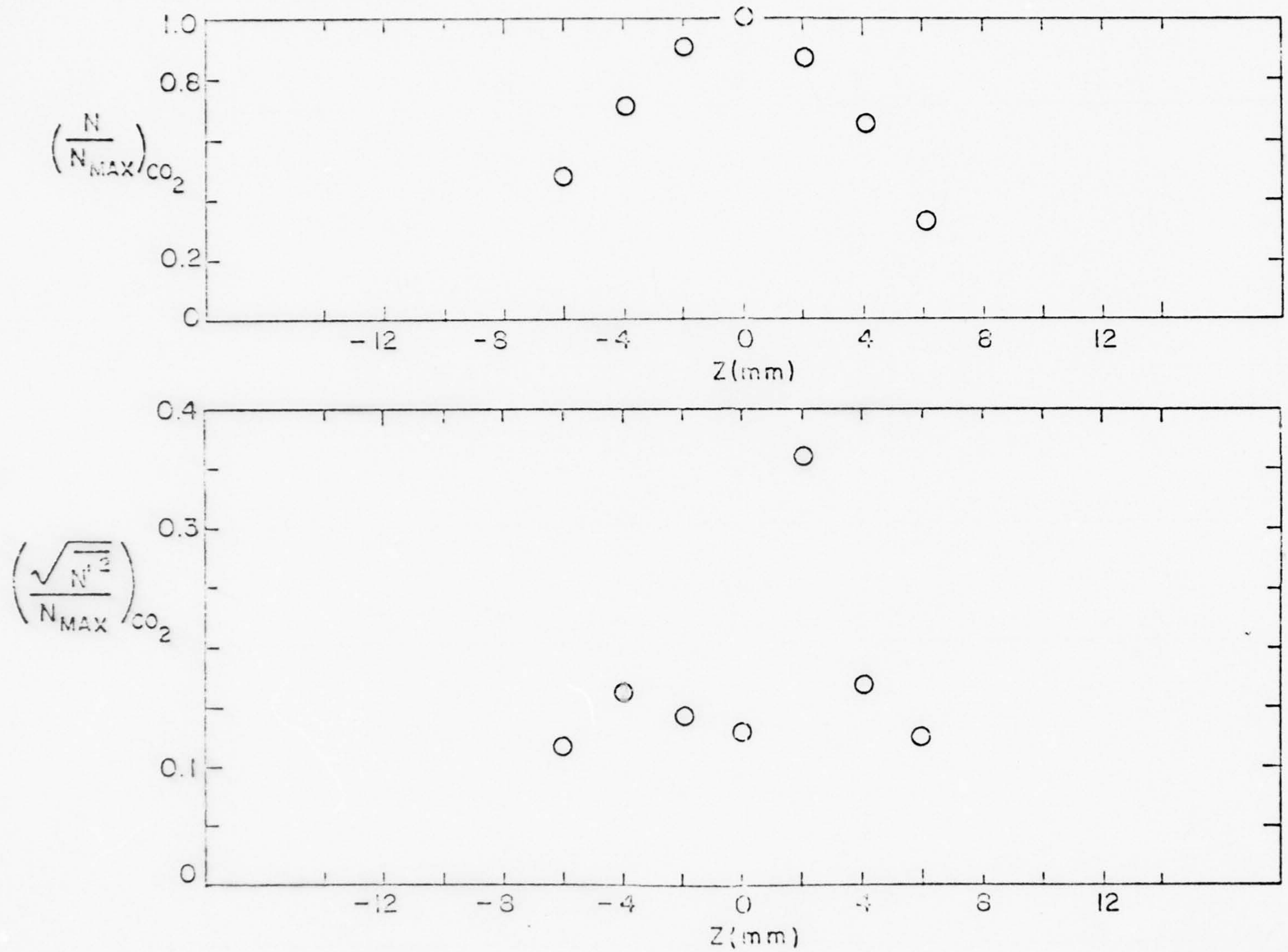
2 N_2 TEMPERATURE FLAME PROFILE AT X/D = 4.546



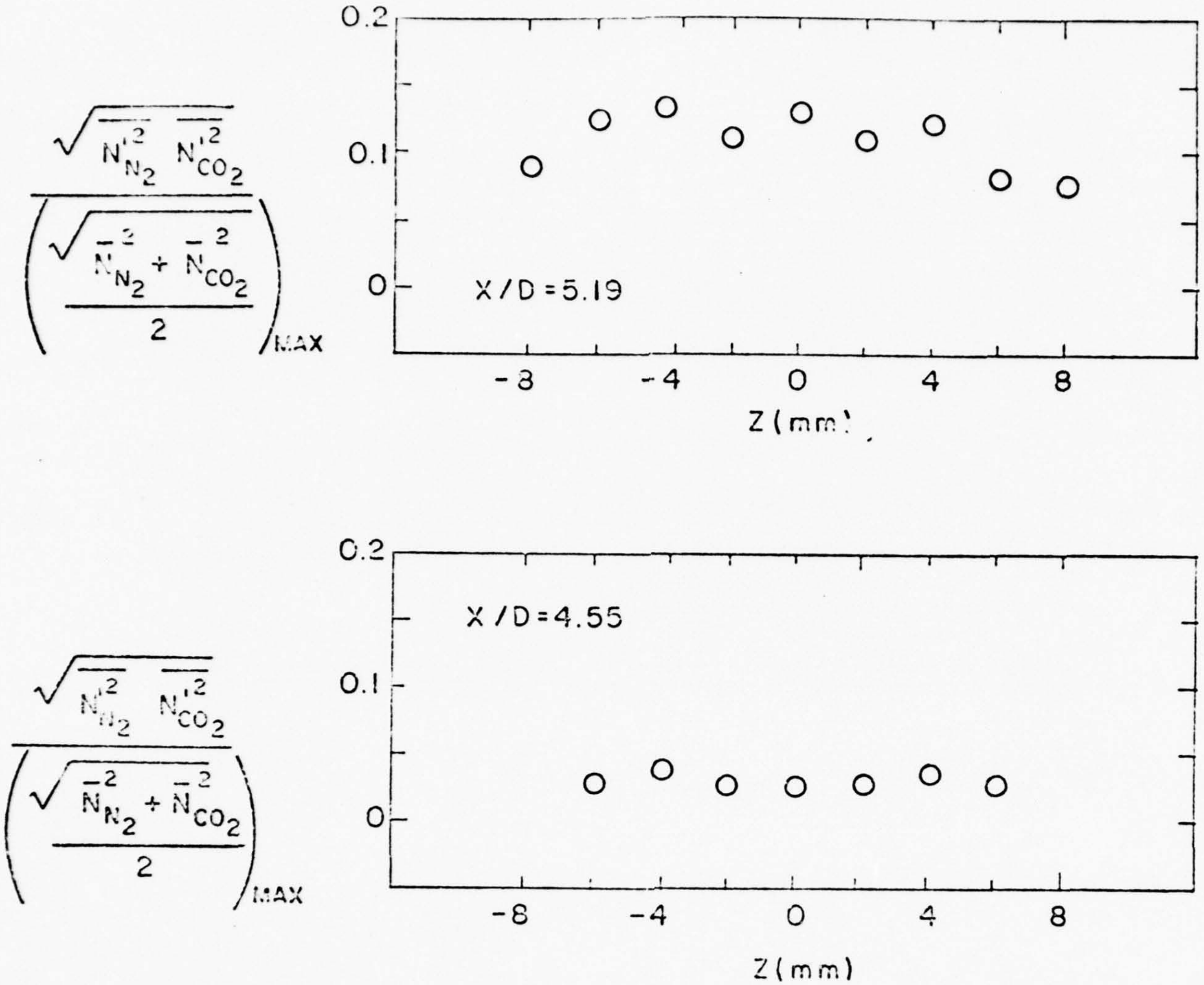
3 N_2 CONCENTRATION FLAME PROFILE AT X/D =4.540



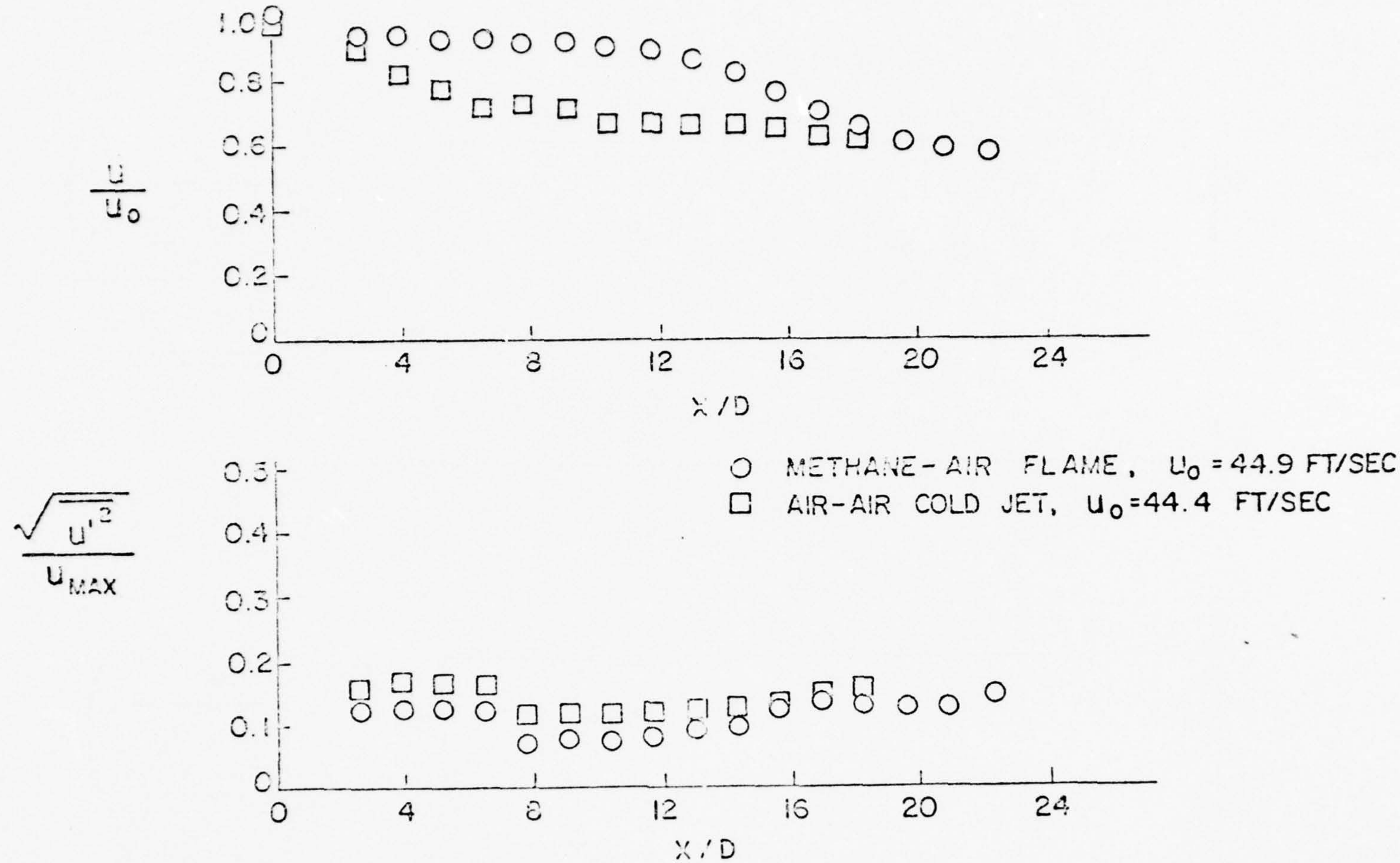
4 CO_2 TEMPERATURE FLAME PROFILE AT X/D = 4.546



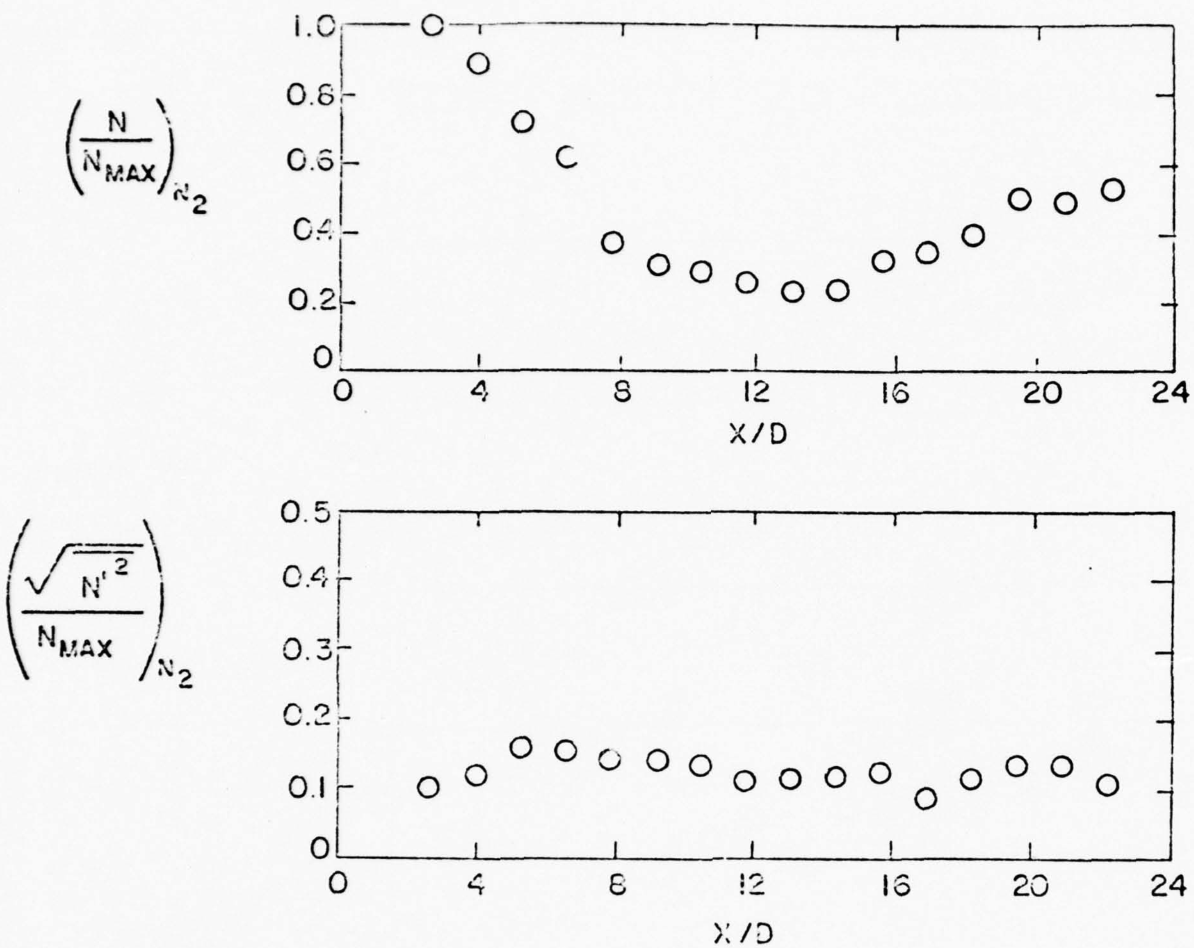
5 CO_2 CONCENTRATION FLAME PROFILE AT X/D = 4.546



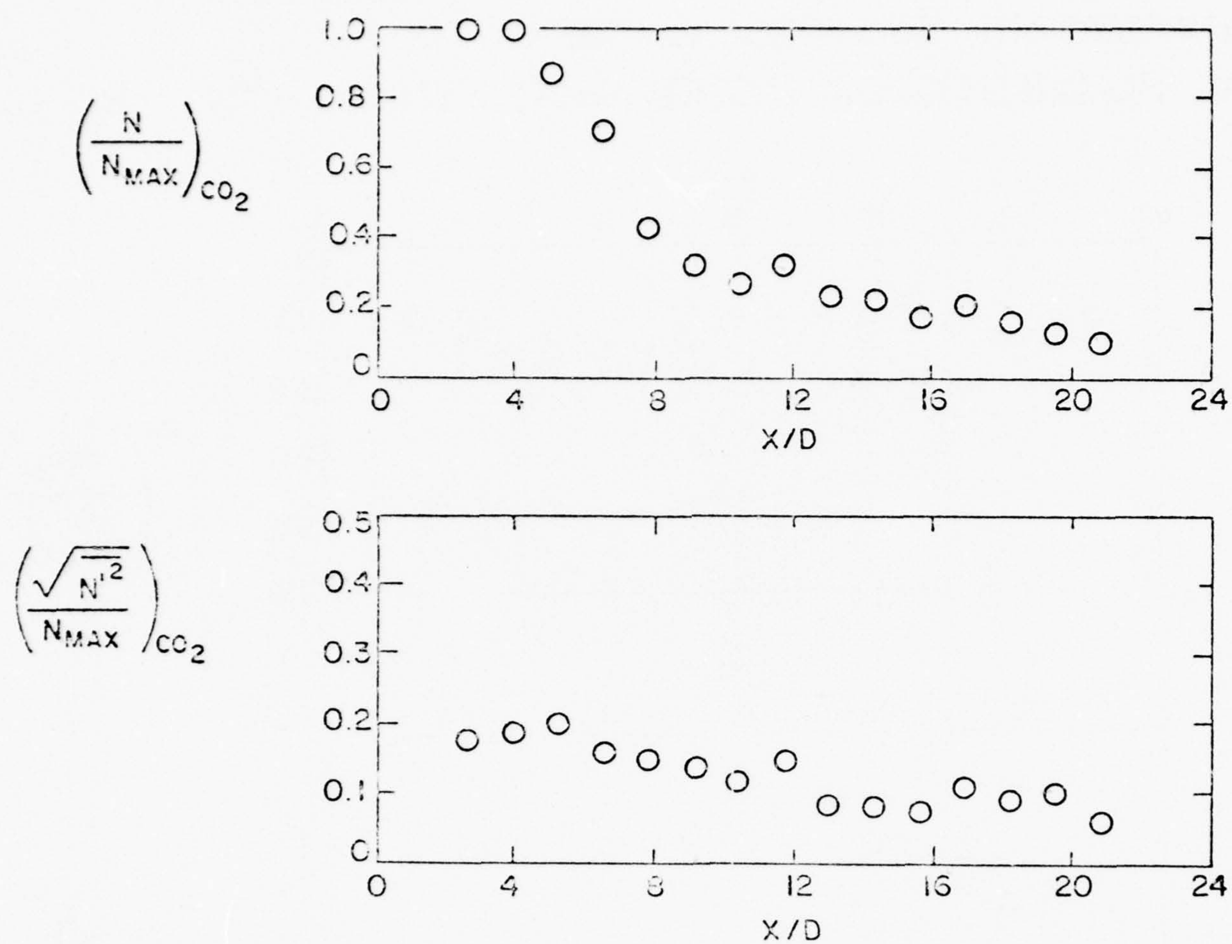
6 $N_2 - CO_2$ CONCENTRATION CROSS CORRELATION IN FLAME



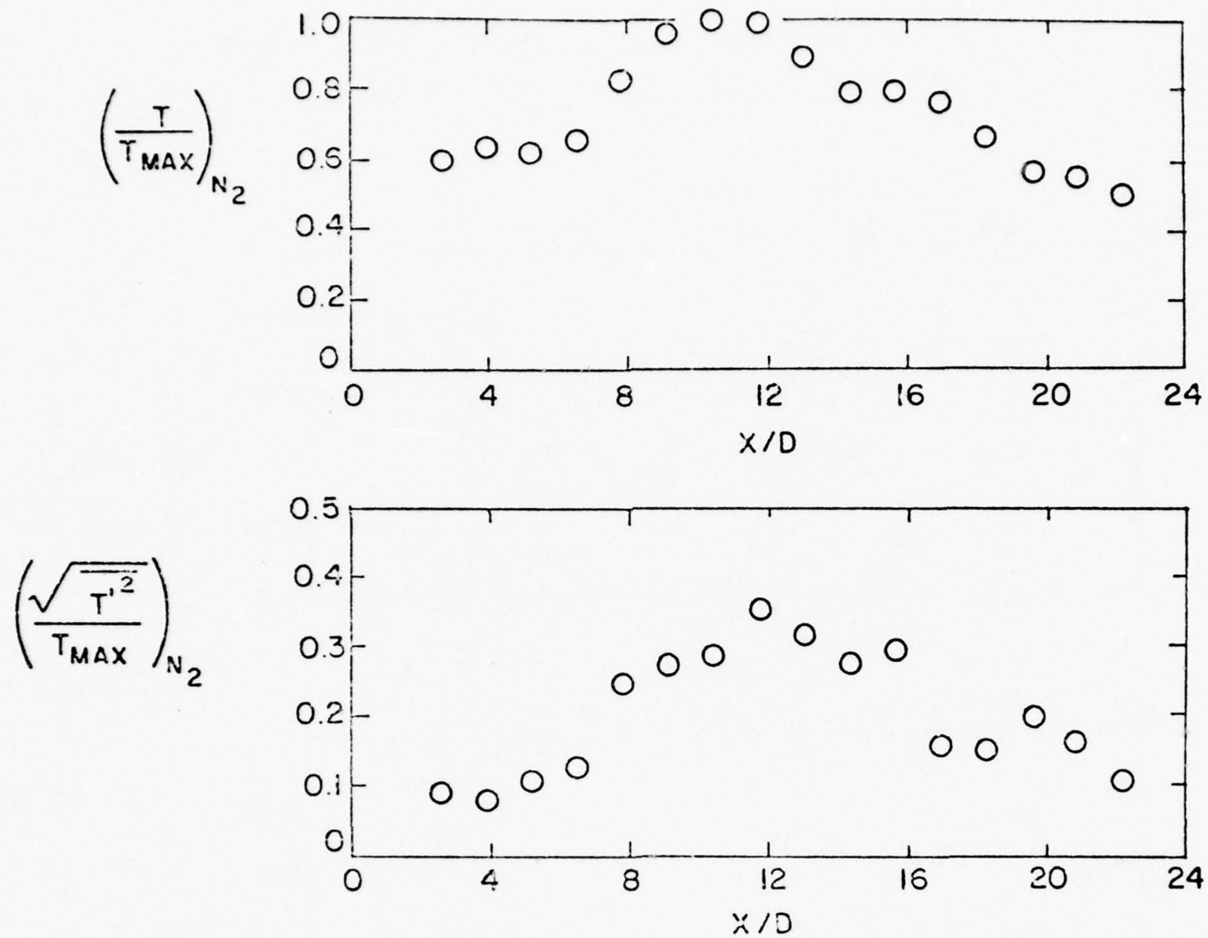
7 AXIAL NORMALIZED VELOCITY AND TURBULENT INT. PROFILES IN METHANE-AIR FLAME AND AIR-AIR COLD JET



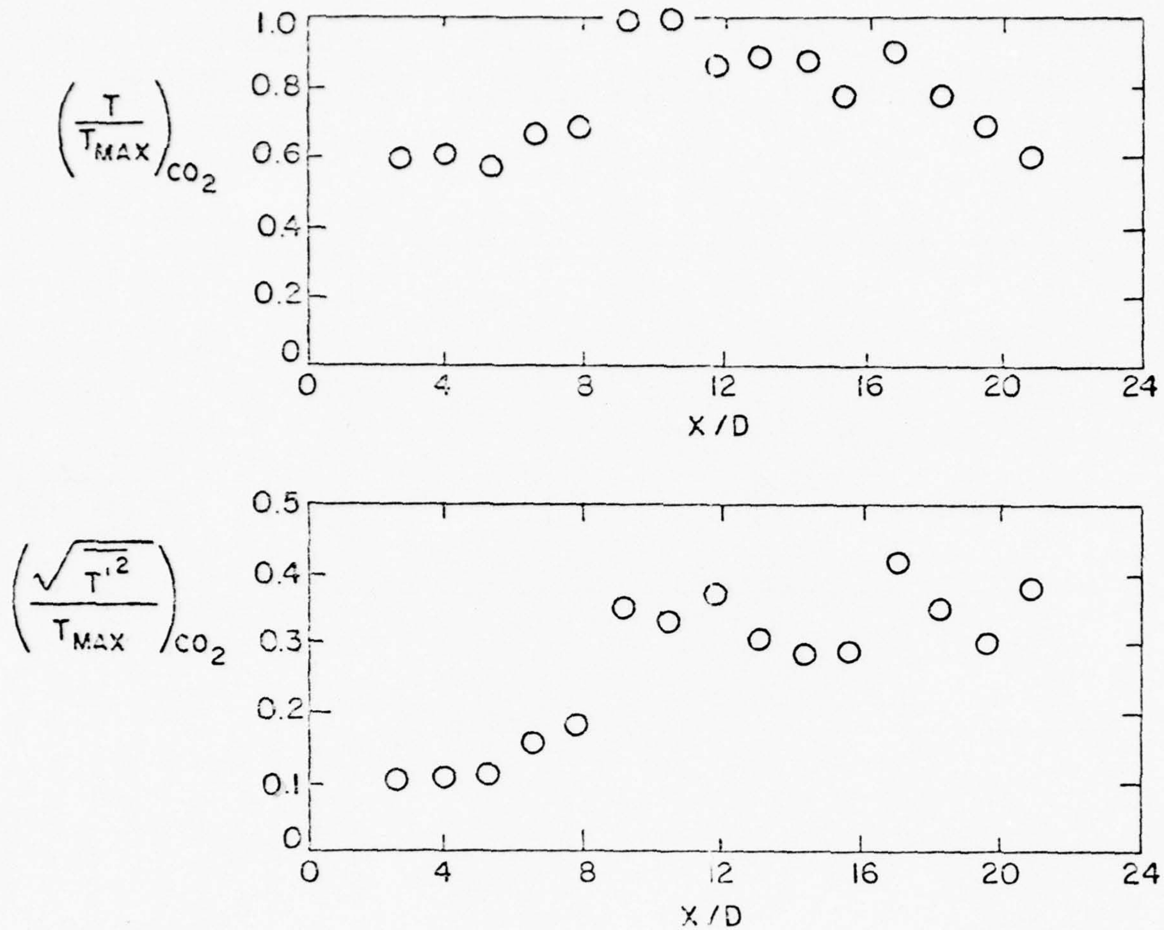
8 N_2 AXIAL NORMALIZED CONCENTRATION AND TURBULENT INTENSITY PROFILES IN METHANE-AIR FLAME



9 CO_2 AXIAL NORMALIZED CONCENTRATION AND TURBULENT INTENSITY PROFILES IN METHANE-AIR FLAME



10 N_2 AXIAL NORMALIZED TEMPERATURE AND TURBULENT INTENSITY PROFILES IN METHANE-AIR FLAME



11 CO_2 AXIAL NORMALIZED TEMPERATURE AND TURBULENT INTENSITY PROFILES IN METHANE-AIR FLAME

LASER RAMAN PROBE FOR COMBUSTION DIAGNOSTICS

General Electric Company, Corporate Research and Development
Schenectady, New York
Subcontract No. 8960-17

Marshall Lapp, Principal Investigator
C. M. Penney, Physicist

Introduction

Further work has been done on the development of both the combustion apparatus used for acquisition of instantaneous temperature data from turbulent combustion flows and on the laser and signal processing apparatus used for obtaining the Raman scattering signals from which the temperature values are derived. Experimental difficulties in these systems have been largely overcome, and experimentation is in progress leading to the desired temperature profiles.

Discussion

We have continued in our program for obtaining instantaneous values of temperature from a turbulent diffusion flame produced in a coaxial jet combustor. This flame, characterized previously by detailed turbulent velocity data obtained from laser velocimetry, is produced on a 2.7 mm-diameter hydrogen fuel jet axially centered in a 100 mm-diameter

air duct. A shear flow results from the dissimilar velocities of these streams, the slower annular air flow being supplied by a blower with subsequent straightening and developing into a turbulent pipe flow.

The instantaneous values of gas temperature are measured from the temperature-sensitive information contained within the vibrational Raman scattering spectrum. The method currently used involves detection of the Stokes and anti-Stokes Q-branch intensities with photomultipliers contained within the polychromator housing of a SPEX Model 1800 spectrometer. The ratio of these signals is dependent upon temperature through the population factor for the first excited vibrational state of the test molecule, nitrogen. (An alternate Raman technique, based upon detection of selected portions of the Stokes or anti-Stokes Q-branches, may also be used for these temperature measurements in a later portion of this program.)

The scattered radiation is produced by excitation from a modified Phase-R 2100 B coaxial flashlamp-pumped dye laser, presently operated in the blue (at 488 nm, to take advantage of calibration from an argon ion laser) through use of coumarin dye. The major modifications include line narrowing and stabilization, and adoption of a real-time laser line shape and spectral position monitor.

Continued routine operation of the dye laser has required significant effort; this device has been made to perform well, but suffers from reliability problems, limited dye lifetime, and a strong degradation of beam quality, spectral purity, and beam intensity when the repetition rate is too high (i.e., when the dye does not have sufficient time

between shots to become quiescent).

Another significant experimental problem is produced by unwanted scattered light in the optical systems, presenting background intensities which reduce experimental sensitivity and which can produce unreliable results. Most of these problems can be alleviated by various experimental procedures, such as careful light baffling, insertion of appropriate optical cutoff filters at different positions in the optical paths, etc. However, spurious signals arising from illumination of the glass walls of the coaxial combustor pipe, while removable by extensive redesign via carefully planned windows (and with a concomitant increase in combustor complexity) have been removed by replacing the test section with an open throat section. A stable and well-defined turbulent diffusion flame is produced by this coaxial jet flow, and the region of this flame probed by Raman scattering lies well within the potential core of the air flow. Any differences between this flow configuration and that associated with the glass pipe test section will be defined by additional studies with laser velocimetry.

Presently, work is in progress using the modified Phase-R laser to produce values of temperature for the open throat combustor tunnel. Work has also started on integrating the Raman apparatus with the laser velocimetry measurement system, leading toward the major goal of this program -- obtaining simultaneous temperature and velocity data which are instantaneous in a fluid mechanic sense (< 1 μsec time resolution) and spatially well-resolved (< 1 mm^3), and which can hopefully provide worthwhile new information on the interactions between combustion processes and turbulent flow.

Notes and References

Recent publications and manuscripts related to this research effort supported by Project SQUID and by other parallel General Electric and government efforts are listed below:

1. M. Lapp and C. M. Penney, "Raman Measurements on Flames," in Advances in Infrared and Raman Spectroscopy, Vol. 3, ed. by R. J. H. Clark and R. E. Hester, Heyden and Son Ltd., London, Chapt. 6, pp. 204-261.

2. M. Lapp, "Raman Scattering from Water Vapor in Flames," to appear in AIAA J., Nov. 1977.

INVESTIGATION OF NOVEL LASER ANEMOMETER AND PARTICLE-SIZING INSTRUMENT

Stanford University, Stanford, California
Subcontract No. 8960-7

Adjunct Professor S. A. Self, Principal Investigator
Dr. D. J. Holve, Research Associate
Mr. C. Van Horn, Research Assistant

Introduction

The objective of this research is the investigation and development of a laser anemometer and particle-sizing instrument capable of making simultaneous, remote, in-situ measurements of velocity and particle size (2-50 μm) in two phase flows, with particular reference to liquid spray combustors. In addition, the instrument should be applicable to particulate laden flows in general, e.g. hot ash flows found in MHD exhaust or frozen ash flows found in the exhaust of a coal-fired power plant.

Discussion

The effort has continued to emphasize the particle-sizing aspect, though some preliminary experiments were performed on the two beam, transit-timing anemometer concept.

Ideally, to count and size particles one at a time in situ, from their light scattering amplitudes, one requires a uniformly illuminated control volume which is rather larger than the largest particles in the distribution, yet small enough to have a low probability of containing two particles simultaneously. This clearly imposes limits on the range of particle size and the concentration that can be accommodated. A second requirement is a signal output which increases monotonically with particle size and is insensitive to particle (complex) refractive index and shape.

In the basic scheme explored earlier in this investigation, use

was made of coaxial forward scatter from a laser beam focus which, for particles greater in diameter than a few wavelengths, yields a total collected scattered signal which is accurately proportional to particle projected area, and is independent of refractive index. The effective control volume is determined by the distribution of intensity about the laser focus, together with the effect of spatial filtering in the collection optics. Inevitably, the intensity distribution along the beam axis falls off much more slowly than in the radial direction, giving rise to an elongated control volume, and, in practice, the spatial filter is not very effective in reducing the length of the control volume. For this reason, use was made of a side scatter channel to gate the forward scatter detection channel, so that only signals from particles close to the focus were processed by the pulse-height analyzer.

As reported earlier, this system was shown to work satisfactorily from calibration experiments using pinholes and also with particles in the range 3-30 μm, dispersed in a liquid flow system. However, further work revealed that this system was only capable of handling very low particle concentrations $\lesssim 10^3$ cm^{-3}. The reason is that with higher concentrations there is a high probability of there being one or more particles in the long illumination volume, and these create a continuous, varying background signal which is superimposed on the occasional signals from particles traversing the center of the control volume and which generate gating signals.

This limitation was regarded as sufficiently restrictive for planned applications, that it warranted a re-examination of the basic scheme. It was concluded that the only practical method of reducing the length of the control volume, to allow for higher concentrations to be handled, was to adopt an off-axis, near-forward scatter geometry in place of the coaxial one, and to eliminate the side scatter gating channel. The effective control volume is then given by the intersection of the laser beam and the "beam-like" viewed volume determined by the spatial filter in the collection optics. For relatively small angles ($\lesssim 10°$) between the axes of illumination and collection, the length of the control volume can be made quite small ($\lesssim 1$ mm).

There are two important consequences of adopting an off-axis scattering geometry. First, the relation between the collected scattered signal and the particle diameter can no longer be simply calculated from diffraction theory, but must be computed from Mie scattering theory for the particular geometry. Moreover, the relation may no longer be monotonic or so insensitive to refractive index. Second, by abandoning the side-scatter gating channel, the effective distribution of illumination in the control volume is no longer nearly uniform, and account must be taken of this in the data reduction scheme.

The first point was investigated by computing the scattered signal as a function of particle diameter for various scattering angles and collection optics, and for various refractive indices using a Mie scattering code. It was established that satisfactory signal-size

characteristics can be obtained that are relatively insensitive to refractive index, provided the scattering angle is kept small ($\lesssim 10°$). These characteristics are not always monotonic, but tend to have a shallow dip in a small size range. Similar behavior is typical of commercial sampling - type particle counter-sizers and is not a significant problem.

The second point, related to the non-uniform illumination intensity is the control volume, is fundamental to any in-situ sizing scheme based on absolute scattering intensity. Monodisperse particles give a distribution of signal amplitudes extending downwards from some maximum amplitude, depending on their exact trajectory through the control volume. A polydispersion will clearly give a superposition of such signal distributions, and the problem then is to unfold the signal amplitude distribution to obtain the particle size distribution. Analytically, such an inversion is possible and unique, but its practical realization in a computer code is not entirely straightforward, and can introduce large and unknown errors. A matrix inversion algorithm has been adapted for the purpose in hand so as to minimize the error.

Experimentally, a near forward scatter system has been set up and tested on monodisperse aerosols of oleic acid, in the size range 2-30 μm, produced by a Berglund-Liu generator. For each size, a signal amplitude count distribution was accumulated in a pulse height analyzer. These distributions displayed a sharp cut-off at a maximum signal amplitude, and these maxima were found to correlate well with the signal amplitude-particle diameter characteristics calculated using the Mie scattering code.

The signal amplitude count distributions were smoothed, to remove statistical fluctuations due to finite sample size, and entered as the matrix elements in the computer inversion algorithm. To test the inversion scheme, experimental signal amplitude count distributions from monodispersions of various sizes were generated and inputted to the inversion program. It was found that the inversion scheme would indeed unfold the broad distribution of signal amplitudes to yield a very narrow distribution of indicated particle diameters of the correct size.

A more critical test of such a particle counter-sizer is whether it will correctly indicate the structure of a polydispersion consisting of the superposition of a number of monodispersions. Such a test was simulated by accumulating the signal amplitude count distributions as the monodisperse particle generator was adjusted sequentially to produce four separate monodispersions between 2 and 30 μm. The accumulated output was inputted to the inversion program and, gratifyingly, the output indeed reproduced the structure of four narrow peaks positioned at the correct sizes.

To summarize, a practical, in-situ, laser scattering particle sizer-counter has been demonstrated that is effective in the size range 2-30 μm, concentrations up to $\sim 10^5$ cm^{-3}, and flow velocities of at least

10 m/sec. By suitable choice of scattering geometry, the scheme should be adaptable to any 15:1 size range between perhaps 1 μm to 50 μm or more. At present the system requires hand collection of data for input to an off-line computer, but it should be a straightforward matter to couple the instrument to an on-line computer for automatic data reduction. The instrument shows a weak sensitivity to refractive index (real part) and a rather stronger sensitivity to particle absorption. For substances which can be used to form a monodisperse aerosol in a suitable particle generator, it would be best to perform a direct calibration over the size range of interest. Alternatively, if the complex refractive index is known, the system response can be calculated using the Mie scattering code.

Full details will be given in a forthcoming technical report.

Semi-Annual Progress Report

LARGE SCALE STRUCTURE AND ENTRAINMENT IN THE TURBULENT MIXING LAYER

University of Southern California, Los Angeles, California
Subcontract No. 8960-12

Professor F. K. Browand, Principal Investigator
Mr. B.O. Latigo, Research Assistant

Introduction

Previous visual observations indicate the presence of large scale, quasi-organized, vortical lumps aligned across the flow (LSS) in the two dimensional mixing layer. The existence of these structures--documented visually over a range of Reynolds numbers extending from 10^3 to 10^7 -- is suggestive of their importance as a characteristic feature of the turbulent flow. As the mixing layer grows downstream, the vortices must necessarily interact to form larger vortices. The interactions-- to a certain degree--are distinct and repeatable, and it is precisely these interactions which are responsible for the growth of the mixing layer. The present experimental study, carried out in a wind tunnel at Reynolds numbers 10^6, is intended to provide more information about this large scale structure.

Discussion

The method for studying large scale structure has been to ensemble average "characteristic events" in the record. "Events" representing

certain phases of the interaction of the large scale structure have been detected by means of two hot-wire probes placed on either side of the mixing layer. The technique is capable of identifying certain features of the large scale interactions, but there are several difficulties. When the events to be detected arise completely from natural development and occur randomly in time, a very long data record is necessary to gather a sufficient number of ensemble members. That is, the mean sampling rate tends to be low. Approximately 25 large scale vortices pass by for every one that is kept. This sampling rate probably cannot be improved much without degrading the sharpness of the ensemble. Furthermore, certain other phases of the interaction are impossible to detect without moving the location of the detector probe relative to the measuring probe. This is perfectly feasible but large data sets -- one for each relative position -- must be generated.

The basic sampling procedure has recently been improved by introducing a small acoustical disturbance at the splitter plate trailing edge with a linear array of speakers which span the tunnel roof. The form of the wave packet disturbance is chosen in a very special way. It is composed of a carrier wave -- at the frequency of the initial instability -- and a modulation envelope whose frequency is related to the average passage frequency at a far downstream location. The purpose is to introduce a disturbance which will augment the naturally occurring interactions without altering their fundamental character. The advantages of using this technique are twofold. First, the sampling rate can be increased significantly. Second, the triggering of each wave packet produces a time reference. Figure 1 gives a preliminary indication of the results achievable by this method of forcing. The first trace is the signal transmitted to the loudspeaker array. The second trace is the longitudinal velocity fluctuation response recorded by a hot-wire placed on the low speed edge of the layer one inch downstream from the plate trailing edge. The result of the loudspeaker forcing is clearly present in the velocity field. The remaining traces at a succession of downstream positions (note time scale change) represent ensemble averages of 256 individual realizations. Two things stand out. First, the ensemble

detects repeatable structure, and this structure appears at the time appropriate for a disturbance convected downstream from the vicinity of the plate trailing edge. Second the velocity traces, at the sequence of downstream stations between 10 and 18 inches, show the formation of a subharmonic clearly. (The Reynolds number at 18 inches is about 5×10^5.) At ten inches downstream, three velocity minima are present in the record, and represent the passage of three individual vortices. The first two are spaced about 10 m seconds apart and have each undergone approximately 3 interactions upstream. Between 10 and 18 inches, these two undergo another interaction consisting of a coalescense or pairing to form a single, large vortex.

The procedure will be first to study various forcing wave shapes in more detail. When we understand the mechanics of the forcing, certain disturbances will be chosen and the ensemble measurements will proceed. Both u' and v' will be measured with an x-wire moved slowly across the mixing layer. These measurements will be repeated at a series of downstream positions to map the complete interaction.

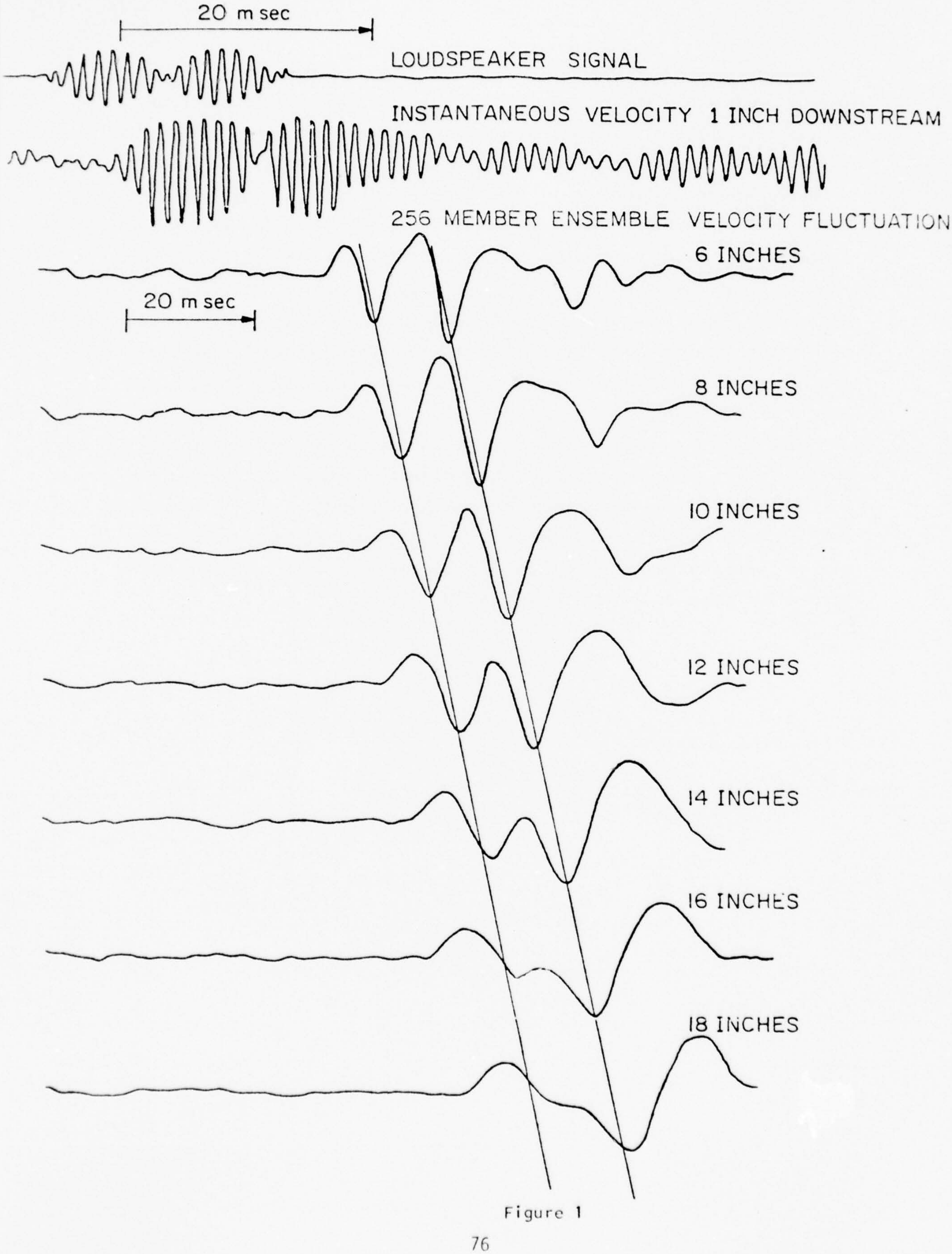

20 m sec
LOUDSPEAKER SIGNAL
INSTANTANEOUS VELOCITY 1 INCH DOWNSTREAM
256 MEMBER ENSEMBLE VELOCITY FLUCTUATION
6 INCHES
20 m sec
8 INCHES
10 INCHES
12 INCHES
14 INCHES
16 INCHES
18 INCHES

Figure 1

IV. TURBULENCE

BINARY GAS MIXING WITH LARGE DENSITY
DIFFERENCE IN HOMOGENEOUS TURBULENCE

Studies of the Basic Phenomena Associated with
Molecular Diffusivity Effects in Turbulent Mixing

Michigan State University, East Lansing, Michigan
Subcontract No. 4964-49

Professor J. F. Foss, Principal Investigator
Mr. K. C. Cornel'us, Graduate Research Assistant

Introduction

It is the purpose of our research to illuminate, and to provide quantitative measures of, the fundamental phenomena which are responsible for the strongly enhanced molecular diffusivity effects in a turbulent mixing field. The presence of these effects is of obvious importance in the combustion process; their full exploitation requires an understanding of their dependence upon the character of the turbulence field. One approach toward this understanding is to examine the results of controlled variations in the governing parameters of experiments which are (1) sufficiently simple that the cause/effect relationships are least ambiguous and (2) sufficiently similar to the technological problem that the phenomena of interest are preserved. Our experiments examine the mixing of two distinct rectangular volumes by light scattering measurements from the central region of a closed mixing chamber. The nature of the experimental facility allows the initial turbulence structure in the two volumes to be individually controlled and stable, unstable or neutral density mixing may be investigated.

Each scan of the mixing region can be executed in ($\geq$) 3.1 msec and the collection optics can be adjusted to examine a scan length (ℓ) of $7.3 \leq \ell \leq 17$ cm. An optical system, which involves a focused incident laser beam, a collection lens system (2 aerial photography camera lenses in series) and a (rotating) disc with four helical slits, is used to define a contiguous set of individual scattering volumes along the length of a given scan. The minimum scattering volume length is defined by the width of the helical slit divided by the cosine of the intersection angle (22-45 degrees) with the vertical scattering line. The nominal length dimension for the experiments completed to date was $\simeq 0.35$ mm. The nominal diameter of the focused laser beam, over the 74 mm scan length, was 0.25 mm. These lengths define the observed scattering volumes for the

previously completed experiments; data were taken from 205 scattering volumes per scan. A recently incorporated improvement is the use of four, small dimension slits which have been bonded to the rotating disc. These slits were drawn 5 x "real size" by a CALCOMP plotter and photographically reduced prior to their fabrication by an acid etching process. A monotonic line broadening was used which partially compensates for the cosine factor in the scattering volume height definition; the resulting scattering volumes are nominally 175 μm for the minimum (7.3 cm) scan length.

Discussion

The essential task of the prior six month reporting period has been the preparation of the technical report on the research carried out during the two years of active SQUID support. This report is quite near completion. The five sections prior to the discussion of results and three appendices are essentially finished. The unfinished work includes computations based upon an alternative model to evaluate the relative extent of the small scale mixing vs. the large scale convective transport of the turbulent motion. In addition, several tests to critically evaluate the striking results of the Fourier transform calculations have been devised and await programming and execution. Consequently, with regard to the progress indicated in the March 1977 Semi Annual Report: i) the etched discs have been obtained with University funds, ii) the quantity YS will be replaced with a more suitable measure of the instantaneous spread about the instantaneous centerline, iii) the high speed integrator circuit for the species concentration measurement has been designed but awaits further support before fabrication can be achieved and iv) the revisions to the physical configurations noted in the January 1977 proposal await additional support before they can be incorporated.

Semi-Annual Progress Report

HETEROGENEOUS TURBULENT FLOWS RELATED TO PROPULSIVE DEVICES

University of California, San Diego
Subcontract No. 4965-26

Paul A. Libby
Principal Investigator

Introduction

This research addresses problems related to the turbulent heterogeneous flows which arise in a variety of propulsive devices when reactants and products mix and react. The effort is both experimental and theoretical; the experimental program concerns exploitation and extension of the multiple sensor "hot wire" technique of Way and Libby which permits time-resolved and space-resolved measurements of velocity and concentration of one light species, e.g., helium, in a mixture of light and heavy gases under isothermal conditions. The application of this technique in the present research is to a confined internal flow corresponding to an idealized combustor. The related theoretical work supports the experimental effort and attempts to extend the results thereof to flow situations of more practical concern, e.g., to chemically reacting flows.

Discussion

In our previous Semi-Annual Progress Report we indicated that our theoretical efforts were directed toward an extension of the Bray-Moss model for premixed turbulent reactions to include the effects of finite but large turbulent Reynolds and Damkohler numbers. The motivation for this extension resides in the presentation of most experimental data on turbulent flames in terms of the ratio of the turbulent to laminar flame speeds. In most theories for such flames, and in particular in the Bray-Moss model, the Reynolds and Damkohler numbers, and thus the laminar flame speed are taken to be infinite; as a consequence the possibilities for comparing theoretical predictions with the extensive body of experimental data on turbulent flames are limited.

During the past six months a perturbation analysis which incorporates the first order effects of large but finite Reynolds and Damkohler numbers has been carried out. The starting point for this analysis is the representation of the molecular transport terms in the conservation equations for the mean product concentration, the intensity of the product fluctuations, and the turbulent kinetic energy, terms which are neglected in the first order analysis. For example, in the equation for the conservation of mean product there arises upon time averaging the term $\overline{\rho D \partial c/\partial x}$ which must be expressed appropriately. With the reasonable assumptions that $\rho D \cong \mu = \rho\nu$ and that $\mu \sim \bar{T}$

$$\overline{\rho D \partial c/dx} \cong \bar{\rho}\tilde{\nu} \frac{\partial \tilde{c}}{\partial x} + \frac{\partial}{\partial x} \overline{\rho\nu c''} - \frac{1}{2} \rho_o \nu_o \tau \frac{\partial}{\partial x} (\overline{\rho c''^2}/\bar{\rho})$$

where $\tilde{c}$ is the mass averaged product concentration, τ is the heat release parameter and the remaining notation is standard. Note that Favre averaging is employed.

The second and third terms on the right can be conveniently expressed in terms of $\tilde{c}$ and correspond to contributions to the transport of mean product due to fluctuations in the viscosity coefficient whereas the first term on the right is the contribution to such transport from the mean viscosity coefficient. It is not possible to model the transport of turbulent kinetic energy due to fluctuations in the viscosity coefficient with the same rigor but we have incorporated the effect in a heuristic manner. The final additional modelling necessitated by the treatment of finite but large Reynolds and Damkohler numbers relates to the inclusion in the scalar dissipation term of a Reynolds number effect.

The resulting analysis is interesting from a formal point of view and has been carried out both for normal flames and for the strong interaction case in which the turbulence generated by the flame overwhelms that in the stream approaching the flame. In each of the two cases the first order solutions, i.e., those already published in references 1 and 2, yield two eigenvalues which are computed as part of the solution; they have direct physical significance, e.g., they yield the turbulent flame speed as a multiple of the square root of an appropriate turbulent kinetic energy. In the perturbation analysis these eigenvalues are likewise perturbed so that we effectively calculate the change in flame speed with finite but large Reynolds and Damkohler numbers, a physically important change.

The analysis of the two cases cited above has been completed, including numerical solutions for a range of values for the heat release parameter τ, and is given in reference 3, at present only partly completed. There remains the interpretation of the results and a comparison with experimental data; work therein is underway.

Our experimental efforts during the past six months have focussed on the two-dimensional jet discharging into a moving airstream. The results of our original experiment have been carried to fruition and presented in reference 4. The most interesting data relate to those establishing the

preferential entrainment of the air on the leeward side of the large turbulent structures. In the case of the jet this is the upstream side of such structure since the turbulent fluid is moving aster than the surrounding airstream. Also of interest and subject to further study is a negative result; we are unable to distinguish between the structure of the helium and velocity interfaces, if we discriminate between turbulent and irrotational fluid on the basis of a level of helium concentration, we might expect, from the low value of the Schmidt number for dilute helium in air, to find the edge of the helium interface further into the irrotational fluid than an interface associated with turbulent velocity fluctuations. However, this was not found to be the case although the interface was found to be statistically considerably thicker than that associated with temperature.

At the present time we are setting up an experiment in which the helium discharging into the airstream will be heated. We thus deal with the fundamentally important case of two scalar mixing. One of the interesting aspects thereof relates to the possibility of distinguishing between the two interfaces, i.e., for helium concentration and for temperature, with their different diffusional characteristics.

References

1. Bray, K. N. C. and Libby, P. A., Interaction Effects in Turbulent Premixed Flames. Phys. of Fluids, 19, 11, November 1976, pp. 1687-1701.

2. Libby, P. A. and Bray, K. N. C., Variable Density Effects in Turbulent Premixed Flames. AIAA J. (accepted)

3. Bray, K. N. C., Moss, J. B. and Libby, P. A., Effects of Finite Reaction Rate and Molecular Transport in Premixed Turbulent Combustion. (Presented at the International Colloquium on Gas-dynamics of Explosions and Reactive Systems, Stockholm August 22-26, 1977 and to be submitted for publication in Acta Astronautica)

4. Anderson, P., LaRue, J. C. and Libby, P. A., Turbulence Measurements of a Two-Dimensional Helium Jet in a Moving Airstream. Office of Naval Research/Project SQUID Technical Report, UCSD-9-PU, 1977.

RESEARCH ON TURBULENT MIXING

California Institute of Technology, Pasadena, California
Subcontract No. 8960-1

Professor A. Roshko, Principal Investigator
Dr. P. E. Dimotakis, Co-Investigator
Mr. Luis P. Bernal, Research Assistant
Mr. Daniel B. Lang, Research Assistant

Introduction

The objective of this research is to obtain a better understanding of the turbulent mixing processes that occur in mixing layers between gas streams of different velocities and densities. Such mixing layers are often a basic element in flows which occur in propulsive devices; examples of problems to which the research is relevant include turbulent combustion, jet noise, and thrust augmentation. The research has proceeded along two parallel lines. On the one hand, we have been making measurements of various statistical properties of the mixing region and their dependence on parameters such as Reynolds number, velocity ratio and density ratio. Such information provides important inputs for engineering models and calculation methods. On the other hand, we have been using the quantitative measurements, e.g., time- and space-resolved concentration measurements, together with flow visualization to identify and describe the physical processes occurring in such mixing regions. Better understanding of the physics is important for the development of more realistic computing models and also for suggesting how turbulent mixing might be controlled or modified.

Discussion

Our research in this reporting period has been addressed mainly to the question of three-dimensionality in plane mixing layers. Previous results from this and other laboratories (Refs. 1, 2) have shown that mixing layers are dominated by large, organized vortices or rollers which are believed to control the growth of the mixing layer. The authors of Refs. 1 and 2 found that these large structures are more or less two-dimensional, i.e., that they have considerable spanwise coherence, as seen for example on flow views normal to the plane of the mixing layer (Refs. 1, 3). The question then is what is the nature of the known three-dimensionality of turbulent mixing layers, how does it become established?

It is the view of Bradshaw (Ref. 4) that mixing layers become increasingly three-dimensional with distance downstream (i.e., increasing Reynolds number), that the coherent structures are vestiges of the initial instability waves, and that at sufficiently high Reynolds number the shear layer will be "fully three-dimensional". There may be some elements of semantic differences here but evidently Bradshaw means that the coherent vortex structures and their characteristic amalgamations or pairings will no longer exist. On the other hand we found (Ref. 5) at values of Reynolds numbers as high as any previously investigated ($U_1 x/\nu \sim 10^6$, and by common consent believed to be fully turbulent) that the large vortical structures were well defined, clearly coherent, amalgamating, etc. just as at Reynolds numbers two orders of magnitude lower. We believe that they are continually created, whatever the Reynolds number or distance downstream, by the driving instability which is basic to the velocity difference $U_1 - U_2$ and the vorticity which it implies. What then is the

nature of the three-dimensionality in the turbulent structure?

Toward an answer to this question and a settlement of the controversy, we have been carrying out two kinds of investigation, one in the gas mixing apparatus used in Refs. 1 and 3 and one in the water channel used in Ref. 6. In the first case we have been investigating the role of secondary instabilities, i.e., development of three-dimensional scales smaller than the main, large-structure scales. In the second case we have been studying the role of spanwise instability and spanwise variations in the large structures and their interactions, which is the role that Bradshaw emphasizes.

In Ref. 1 streamwise streaks, normal to the spanwise axes of the large vortices, were noted on plan views of the mixing layer, and in Ref. 3 these were associated with a critical Reynolds number above which internal mixing is enhanced although no change in the spreading rate is observed. The streaks were thought to be the edges of streamwise vortices which arise from a secondary instability of the Görtler-Taylor type, and it was suggested that the critical Reynolds number is in some way associated with their development. They were also put forward as a principal mechanism in the development of three-dimensional motions in the flow.

In the present experiments, high speed motion pictures, as well as long-exposure stills, of simultaneous views normal and edgewise to the mixing layer were obtained, in order to see how the streamwise structures are varying, spatially and temporally. The long exposure stills were actually obtained from multiple spark shadowgraph exposures on a single plate. Up to 25 exposures at 1/10 sec intervals were made for each picture. In the view normal to the plane of the mixing layer, these time

averaged pictures still show a pattern of streamwise streaks, now somewhat diffused as compared to the sharp lines in single spark pictures. From these and from the motion pictures it is clear that streamwise structures are located at spanwise positions which are fixed in time. In the multiple exposure pictures they terminate, lose coherence, at a distance downstream which corresponds to the critical Reynolds number determined from the mixing experiments (Ref. 3), i.e., $\Delta U\delta/\nu = 2 \times 10^4$. Their origin is at a position corresponding to a Reynolds number about 0.4×10^4. Of course their beginning and termination is not sharply defined but varies from streak to streak, especially the locations of downstream termination. From this evidence it appears that the streamwise vortices, if that is what they are, develop (amplify) from a pattern of spatial disturbances in the flow, possibly in the boundary layer of the splitter plate. At first there is no appreciable effect on the mixing layer, but at the downstream position of termination or incoherence, corresponding to the critical Reynolds number, the increase in internal mixing is complete. From this and from the motion pictures, it appears that at the critical Reynolds number the streamwise vortices have themselves become unstable from interactions with a main spanwise structure. Correspondingly, single exposure pictures show small scale, typically "turbulent" patterns superimposed on the large structure. The enhancement of internal mixing seems to be associated with these instabilities inside the main structures.

In the second approach to the investigation of three-dimensionality, a mixing layer was established in the GALCIT Free Surface Water Tunnel, as in Ref. 6; dye flow visualization and a laser-Doppler anemometer were used to study the spanwise structure. Our laser-Doppler anemometer was

modified (by splitting the beam and introducing a double focus lens) to produce measuring points at two spanwise locations 22 cm apart and measurements were made at streamwise locations x = 18, 42 and 80 cm, respectively, which are downstream of the position of critical Reynolds number. Pictures from the dye visualization showed that the amalgamation processes at those locations were not two dimensional; that is, the vortices did not remain perfectly normal to the flow direction, and pairing or tripling processes did not proceed in phase along the span. Examples of the helical pairing processes reported by Bradshaw (Ref. 4) were observed. These spanwise non parallelisms obviously contribute to decrease of spanwise correlation averages; secondary instability motions of the kind described above must contribute further to loss of correlation. These factors however do not necessarily imply a breakdown to three-dimensionality; the large structures still have spanwise coherence, albeit not perfectly normal to the flow direction, especially during an amalgamation process. Free stream turbulence would undoubtedly encourage such spanwise variations. But the important point is that the large vortical structures reorganize themselves as the flow proceeds downstream, even in the presence of the spanwise perturbations occurring during amalgamations and in the presence of disturbances from the secondary instabilities occurring on a smaller scale. We believe that the latter are more important than the former as contributors to the pertinent aspects of turbulence three-dimensionality, especially to mixing.

While progress in sorting out its various aspects has been made, the various parts of the picture of three-dimensionality are not yet sufficiently well defined. To describe three-dimensional effects quantitatively is evidently not easy. In classical correlation measurements too much information about the physical structure and processes is lost. We

continue to rely heavily on flow visualization, subjected to quantitative measurement as much as possible and aided by judicious application of probe measurements, to elucidate the physical mechanisms. Once these are understood, the results of more detailed correlation measurements (like those in Ref. 3) can be rationalized and understood.

References

1. Brown, G. L. and Roshko, A. 1974 On density effects and large structure in turbulent mixing layers. J. of Fluid Mechanics 64, 775-816.

2. Winant, C. D. and Browand, F. K. 1974 Vortex pairing: the mechanism of turbulent mixing-layer growth at moderate Reynolds number. J. of Fluid Mechanics 63, 237-255.

3. Konrad, John Harrison 1976 An Experimental Investigation of Mixing in Two-Dimensional Turbulent Shear Flows with Applications to Diffusion-Limited Chemical Reactions. Project SQUID Technical Report CIT-8-PU.

4. Bradshaw, Peter 1976 Interacting Shear Layers in Turbomachines and Diffusers. Turbulence in Internal Flows, Turbomachinery and Other Applications, Proceedings of a Workshop (S. N. B. Murthy, ed.). 35-65.

5. Roshko, A. 1976 Structure of Turbulent Shear Flows: A New Look. AIAA Journal 14, October, 1349-1357.

6. Dimotakis, P. E. and Brown, G. L. 1976 The mixing layer at high Reynolds number: large-structure dynamics and entrainment. J. of Fluid Mechanics 78, 535-560.

Semi-Annual Progress Report

for the Period March 15, 1977 to September 15, 1977

SWIRLING HEATED TURBULENT FLOWS

AS RELATED TO COMBUSTION CHAMBERS

Mahinder S. Uberoi, Principal Investigator

1. Measurement Techniques

A unique shooting hot-wire probe has been developed for the present study. As opposed to the standard method of using a stationary hot-wire probe, the present probe is shot through the flow field at a very high speed (50 ft/sec.) relative to jet speed to yield instantaneous velocity and temperature profiles across a 2-D jet. The probe itself has a standard x-wire for velocity measurements and a single fine platinum resistance thermometer for temperature measurements. Since instantaneous profiles can readily be used to compute instantaneous (turbulent) mass flow, this information reveals fluctuations in entrainment. Some of the other advantages of this technique are: (1) detection of interface foldovers, (2) statistical information about the fluctuations in the width, and the lateral movement of the het as a whole, (3) calculation of dissipation without resorting to Taylors Hypothesis (which is usually not valid for jet-type of flows).

To improve the frequency response and signal to noise ratio of the temperature signal it was decided to use the 1.27μ (Pt.10% Rh) hot wire. Its time constant was determined by exciting the bridge with sine waves. An electronic compensator was then built which proved to

be quite satisfactory. This fine wire has so far survived more than 120 shots without damage.

Since the jet is heated, the velocity signals are obviously contaminated with temperature. To find out the errors involved, a detailed analysis was carried out. Assuming a maximum temperature change of 10^{o}C., it was found that the error in U (longitudinal component of velocity) is 12% while V differs from the true V by about 400%. The maximum temperature difference at the measuring section is 8.0^{o} C; and since our present aim is to record simultaneous U, θ signals only, it seems we can get by without temperature compensating our velocity signal.

Currently we are also doing some preliminary investigating of the effects of probe size and needle spacing on velocity (U and V) measurements. We are using a mechanical shaker for dynamic calibration of the probe, while grid generated turbulence and the relation $\overline{(\partial V/\partial t)^2} = 2\overline{(\partial U/\partial t)^2}$ serve as a test for the probe.

2. Fluctuations in Mass Flow and Entrainment

Initial preliminary measurements of instantaneous U, θ profiles across the 2-D jet show large (100%) fluctuations in the turbulent mass flow, and hence the entrainment. The sample size was, however, too small to get a reasonable probability density function of the entrainment. A bimodal distribution, for example, would indicate that significant entrainment occurs in bursts. Nevertheless, these preliminary results are encouraging, and further effort in this direction should prove fruitful.

Using a conventional stationary probe and intermittency detector it was found that for a round jet the non-turbulent mass flow is about 10% of the total mass flow.

3. Study of Turbulent - Non-turbulent Interface

We have found by using shadowgraph and hot-wire measurements that the flow has a periodic structure near the exit of a two-dimensional jet. Small perturbations grow until they become the size of the jet width and are invariably symmetric with respect to the jet center line. This regular structure breaks down a few diameters downstream of the jet. Shadowgraph and hot-wire measurements do not reveal any periodic structure beyond this point of transition.

At low Reynolds numbers the disturbances grow initially very slowly, suddenly becoming very large. A shadowgraph obtained with a time exposure shows a tree-like structure and the length of the trunk depends on the Reynolds number. More precisely, the thickness of the two free boundary layers determine the rate of growth of the initial disturbance.

We have studied the initial structure and the fully turbulent region by using a shooting probe in order to study the universal characteristics of the interface. We need to go a suitable distance from the jet exit where the traces of any initial periodic disturbance have disappeared.

4. Analytical Studies of Swirling Flows

Based on our experimental work and theoretical studies there exist two types of flows.

A swirl flow where the circulation at large radii is zero. This type of flow behaves very much like ordinary sheer flow. We have developed a theory which has been published in The Physics of Fluids.

The second type of flow is charactized by a non-zero circulation at large radii. First we show that such a flow is always stable, unless there is an axial velocity difference between the core and the surrounding flow. We do not show that certain terms in the equation for the angular momentum must be included which have been invariably neglected. These results will be published in the October issue of The Physics of Fluids.

These considerations have a fundamental influence on the swirling flows in general and swirling flows with combustion in particular.

SECOND-ORDER CLOSURE MODELING OF TURBULENT COMBUSTION

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Princeton, New Jersey

Ashok K. Varma, Principal Investigator

Introduction

The interaction between turbulence and chemistry is of considerable importance in determining combustion efficiency and pollutant formation as well as other combustion characteristics in many combustion and propulsion systems. This research program is directed towards the study of the turbulence-chemistry interaction using a complete second-order closure approach.

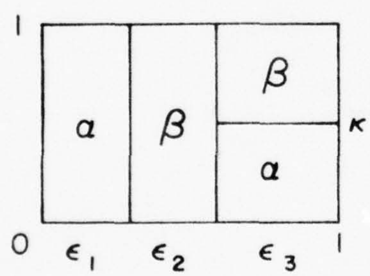
A second-order closure procedure requires the development of closure models for the higher-order correlations that appear in the transport equations for the means and the second-order correlations. A particularly difficult problem is the development of models for the higher-order scalar correlations. A.R.A.P. has proposed a "typical eddy" model for the joint probability density function for all the scalars, which represents the pdf by a set of delta functions of variable strengths and positions in the scalar phase space. Progress towards the development of this model and construction of a complete second-order closure computer program for turbulent reacting flows is discussed in this report.

Discussion

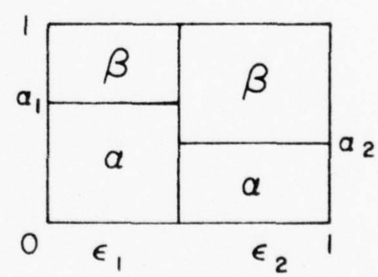
During the past six months advances have been made in three related areas.

"Typical Eddy" model development. The analytical solution for the nonlinear equations of the two species model was discussed in the previous semi-annual progress report (Ref. 1). We have succeeded in narrowing down further the statistical bounds on the set of four correlations $\bar{\alpha}$, $\overline{\alpha^2}$, $\overline{s\alpha}$, and $\overline{s^2}$. The concept of a "most mixed" and "most unmixed" pdf structure to obtain these limits has been developed. This formulation will be useful when the model for three species is developed. In brief, the concept can be explained as follows. If three moments $\bar{\alpha}$, $\overline{\alpha^2}$ and $\overline{s\alpha}$ are specified, the limits on $\overline{s^2}$ can be obtained by constructing the "most mixed" and "most unmixed" pdf's using the information provided by the specified moments. These pdf's are sketched below. The cell parameters, ε_1 , ε_2

Given $\bar{\alpha}$, $\overline{\alpha^2}$, $\overline{s\alpha}$



"most unmixed"



"most mixed"

and κ in one case and ε_1 , α_1 and α_2 in the other can be calculated using the three specified moments. Then the minimum and maximum values of $\overline{s^2}$ that are permissible with the specified values of other moments can be calculated from the above pdf's. The expressions are quite long and are not detailed here. These new limits for $\overline{s^2}$ are narrower than those reported in Ref. 1. The limits on the other moments are correct as listed previously.

The analytical solution for the two species typical eddy model shows that a rational solution for the strengths and positions of the delta functions ($\varepsilon_i > 0$, $0 \leq \kappa \leq 1$) can always be found for sets of moments within the statistical constraints. The analytical solutions have α_3 , the proportion of α in the third cell, as a parameter and we find that an arbitrary specification of α_3 (e.g., 1/2) is not valid over the entire range of moments. However, in general, valid solutions are obtained for a range of values of α_3 . The following procedure is being adopted for the selection of α_3 . The third moments $\overline{\alpha^3}$, $\overline{s\alpha^2}$, $\overline{s^2\alpha}$ and $\overline{s^3}$ are calculated for all valid values of α_3 . We then select α_3 corresponding to the midrange value of the third moments. The $\overline{s^3}$ moment is used for this purpose.

We are currently working on the formulation of the statistical constraints for the three species system. These will be very useful in checking the solution procedure for the three species model. An analytical solution of the three species system appears difficult, but a numerical solution has already been programmed.

Second-order closure program development. The use of the complete "typical eddy" model in our reacting shear layer (RSL) program requires the additional solution of the transport equations for the second-order density correlations $\overline{\rho'\rho'}$, $\overline{\rho'h'}$, $\overline{\rho'\alpha'}$ and $\overline{\rho'\beta'}$. The transport equations have been derived and modeled in tensor form. These equations now have to be cast into an axisymmetric coordinate system and the boundary layer approximations used to obtain the equations that will be solved numerically in the program. This work is proceeding rapidly and the program including the density correlation equations should be operational in the near future.

Recent program calculations. Some recent program calculations demonstrating the important turbulence-chemistry interaction were described in a paper presented at the Sixth International Colloquium on Gasdynamics of Explosions and Reactive Systems at Stockholm, Sweden (Ref. 2). The importance of the mixedness correlation $\overline{\alpha'\beta'}$ in turbulent

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diffusion flames has been discussed in previous A.R.A.P. studies (Refs. 3,4). The RSL program now also includes the effect of correlations involving the specific reaction rate, k , fluctuations and the paper discusses the effect of these terms for computations of diffusion and premixed flames. The calculations use the "secondary" model for the higher-order scalar correlations. The correlation $\overline{T'\alpha'}$ (or $\overline{k'\alpha'}$) is negative over most of the flowfield and when these terms are included in the mean chemical source term, there is a marked reduction in the reaction rate. Figures 1 and 2 summarize the results. Figure 1 shows the development of the maximum flame temperature in an exothermic reacting shear layer and illustrates the order of magnitude of the changes in the predictions when the species and temperature fluctuations are properly included in the chemical source terms. Figure 2 shows the change in the flame development in a turbulent premixed reacting flow when the temperature fluctuations are included in the analysis.

These calculations further demonstrate the importance of considering the species and temperature fluctuations in a turbulent reacting flowfield. However, the lack of a suitable pdf model necessitates the use of an unrealistic "model" for higher-order scalar correlations (namely, setting them zero) at this time. The development of the "typical eddy" model as a possible, viable pdf model is important and work on model development is continuing rapidly.

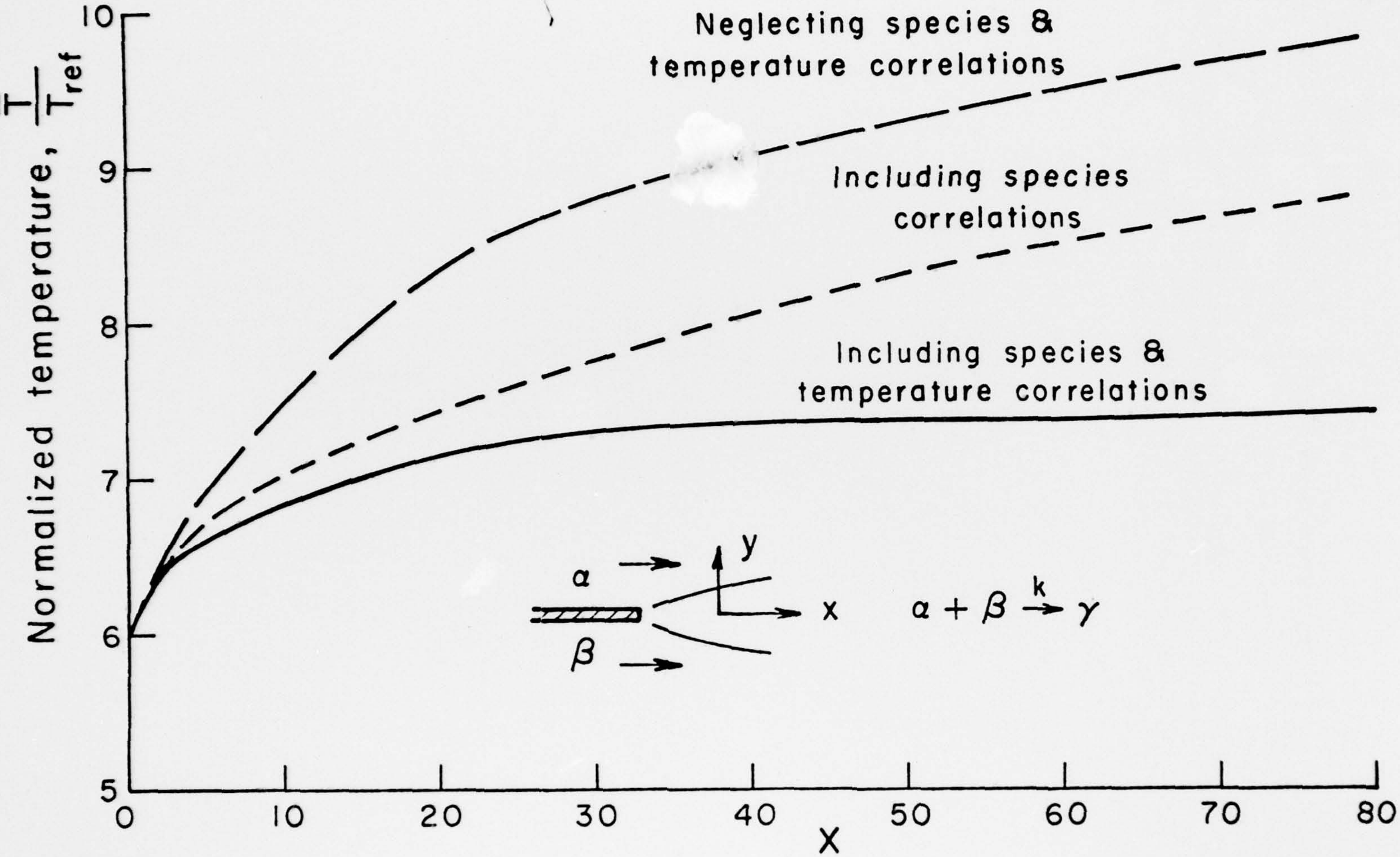
References

1. Varma, A.K., "Second-Order Closure Modeling of Turbulent Combustion," Project SQUID, Semi-Annual Progress Report, April 1, 1977, Project SQUID Headquarters, Purdue University, W. Lafayett, Indiana.

2. Fishburne, E.S. and A.K. Varma, "Investigations of Chemical Reactions in Turbulent Media," Paper presented at the Sixth International Colloquium on Gasdynamics of Explosions and Reactive Systems, Stockholm, Sweden, August 22-26, 1977.

3. Varma, A.K., R.A. Beddini, and E.S. Fishburne, "Second-Order Closure Analysis of Turbulent Reacting Flows," Proceedings of the 1976 Heat Transfer and Fluid Mechanics Institute (A.A. McKillop, J.W. Baughn, H.A. Dwyer, eds.), Stanford University Press, 1976.

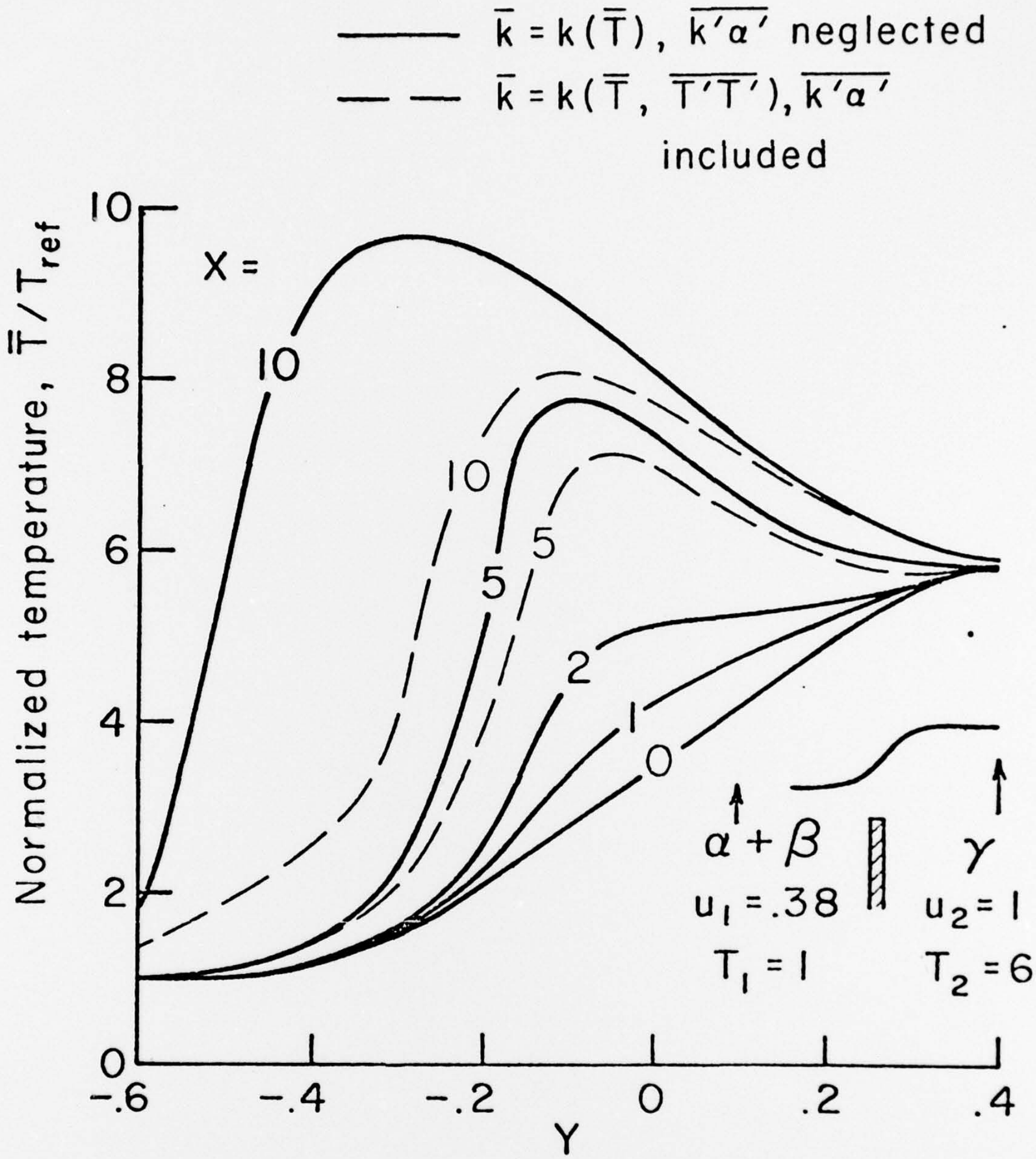
4. Varma, A.K., E.S. Fishburne, and C.duP. Donaldson, "Aspects of Turbulent Combustion," AIAA Paper 77-100, Paper presented at the AIAA 15th Aerospace Sciences Meeting, Los Angeles, CA, January 24-26, 1977.



AXIAL DEVELOPMENT OF MAXIMUM FLAME TEMPERATURE

Reacting shear layer with heat release

Figure 1.



FLAME PROPAGATION IN TURBULENT FLOW

Premixed reacting flow

Figure 2.

V. INDEX BY CONTRACTOR

INDEX BY CONTRACTOR

APPENDIX A

TECHNICAL REPORTS

SQUID TECHNICAL REPORTS ISSUED SINCE 1 APRIL 1977

SQUID Number	Title and Author(s)	ADA Number
AC-16-PU	HTFFR Kinetics Studies of Al + $CO_2 \rightarrow AlO$ + CO from 300 to 1800K A Non-Arrhenius Reaction by Arthur Fontijn and William Felder. March 1977. Issued April 1977.	ADA039001
MICH-17-PU	Unsteady Transonic Flows with Shock Waves in an Asymmetric Channel by John S.-K. Chan and T. C. Adamson, Jr. May 1977.	ADA040846
UMO-2-PU	A Shock Tube Study of the $H_2/O_2/CO/Ar$ and $H_2/N_2O/CO/Ar$ Systems by Anthony M. Dean, Don C. Steiner and Edward E. Wang. May 1977.	ADA041340
PU-R1-77	Turbulence on Internal Flows, SQUID Workshop held June 14-15, 1976, Edited by S.N.B. Murthy. May 1977.	ADA040966
UCSD-9-PU	Turbulence Measurements of a Two-Dimensional Helium Jet in a Moving Airstream by Paul Anderson, John C. LaRue and Paul A. Libby. July 1977.	A043041
MICH-18-PU	Summary of the Project SQUID Workshop on Transonic Flow Problems in Turbomachinery, February 11-12, 1976 by T. C. Adamson.	ADA043317

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Combustion and Chemical Kinetics
Measurements
Turbulence

Progress on

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Reports of progress during the past six months on the 20 research programs comprising Project SQUID are presented. The research programs fall into the areas of Aerodynamics and Turbomachinery, Combustion and Chemical Kinetics, Measurements and Turbulence. Project SQUID is a cooperative program of basic research related to jet propulsion. It is administered by Purdue University and sponsored by the Office of Naval Research.

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